Data-Driven Pavement Maintenance and Rehabilitation Strategies for a New State Route Prioritization System

A Thesis
Presented to
The Academic Faculty

By

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In Partial Fulfillment
Of the Requirements for the Degree
Master of Science in the
School of Civil and Environmental Engineering

Georgia Institute of Technology
August 2018

Data-Driven Pavement Maintenance and Rehabilitation Strategies for a New State Route Prioritization System

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To God and the curiosity he has instilled in me.

ACKNOWLEDGEMENTS

I would like to acknowledge Dr. James Tsai for his generous support academically and professionally for the past two years. His advisement went far beyond solving research problems; his guidance transformed how I think about systems in the world. For that, I am extremely grateful. I would also like to thank Dr. Zhaohua Wang whose ability to understand the details of any problem and general knowledge has provided me with a more focused and practical approach to research. I feel his critiques and insights were crucial in helping me better distill issues with procedures, improve my professional writing, and question results.

I also wish to thank some other key researchers who have helped me throughout my time here. I am grateful for Yiching Wu's support with an assortment of research issues and her patience in helping me figure out better ways to conduct research. I would also like to thank Dr. Chengbo Ai and Dr. Ross Wang who were tremendous in helping me acclimate to the lab through their vast knowledge.

I thank all the members of the lab that have encouraged me and kept me sane throughout my two years here. Many thanks to April who has been my go-to for advice about all aspects of my life, to Georgene who has given me countless ideas and resources while also being an inspiration professionally, to Cibi for helping me keep calm and collected about research and general life, to Vincent who has solved many of my computing problems and who's love of the van will never go unnoticed, to Nora whose sarcasm kept me laughing, to Bo for his wisdom and positivity while picking up aggregates on the side of the road, to Anirban for generally knowing everything I could ever ask, and for all the others who have come and gone sharing perspective, laughter, and lunch along the way.

I'd also like to thank the friends, colleagues, and family who have provided me with different perspectives and advice throughout this journey. A special thanks to my sister, Heather, who has heard it all and helped me navigate the process with confidence and love.

Finally, I would like to thank Matthew for his loving support and loyalty. I appreciated every moment you spent listening to my issues with this endeavor despite never knowing what I was talking about. Your thoughtfulness and "there-theres" will always be cherished

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure 47. Network composite rating for long-term Need Analysis for suggested state

performance standards

LIST OF SYMBOLS AND ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHO	American Association of State Highway Officials
AAER	Annual Average Escalating Rate
COPACES	Computerized Pavement Condition Evaluation System
DOT	Department of Transportation
ESAL	Equivalent Single Axel Load
FAST	Fixing America's Surface Transportation
FHWA	Federal Highway Administration
FY	Fiscal Year
GAMS	Georgia Asset Management System
GDOT	Georgia Department of Transportation
IRI	International Roughness Index
IHS	Interstate Highway System
MAP-21	Moving Ahead for Progress in the 21^{st} Century
MR&R	Maintenance, Rehabilitation, and Reconstruction
NHS	National Highway System
NHPP	National Highway Performance Program
OM	Office of Maintenance
OMR	Office of Material and Research
PACES	Pavement Condition Evaluation System
PCI	Pavement Condition Index

PMS	Pavement Management System
PSI	Present Serviceability Index
PSR	Pavement Serviceability Rating
TPM	Transition Probability Matrix

SUMMARY

Background and Need

With the introduction of the Moving Ahead for Progress in the 21st Century (MAP-21) Act and the Fixing America's Surface Transportation (FAST) Act within the United States, policy has created a need to utilize pavement condition data to inform a state's pavement management and maintenance decision-making. Each of the two federal laws, supported by the Federal Highway Administration (FHWA) and signed by Congress, were created to ensure better maintenance and preservation of the nearly 164,000 miles of federally-supported roadways. The Georgia Department of Transportation (GDOT) has been ahead of the legislative trend towards data-driven decision-making, utilizing a Markovian model based on historical pavement condition survey data since 2009. The model was developed under Research Project 05-19 to make decisions about pavement preservation and to support state budgets that enable maintenance, rehabilitation, and reconstruction (MR&R) activities to be carried out. The model, which is still in use today, adequately predicts the pavement performance of the nearly 18,000 centerline miles of state-maintained routes by using the historical pavement condition surveys within the Computerized Pavement Condition Evaluation System (COPACES) and MR&R expenditure data from Fiscal Year (FY) 1999-FY 2007. While the model can still predict budgets required to preserve a network of pavements to a specified performance level, the availability of new historical condition survey data, state route priority policies, and more current expenditure data can enhance the accuracy and usefulness of the model.

Through the introduction of new data and policies, the existing model will be evaluated and updated. In doing so, the following will be explored:

1. **Introduction of state route priority policy into a pavement management system:** The implementation of a new state route priority system that categorizes state-owned interstate and non-interstate roadways into Critical, High, Medium, or Low priority classifications will be explored for the creation of an updated pavement management model. The classification's use in creating like pavement "families" for pavement deterioration modeling will be explored.

2. **Exploration of best practices for modeling in pavement management systems:** An extensive literature review of new pavement management systems and models will be explored to determine if the existing model is still the best choice.

3. **Creation of new methods for implementing expenditure data into pavement management model**: Previously, limited amounts of pavement MR&R expenditure data were available for use in calculating unit costs and annual escalation rates. This report aims to improve the previously used methods for determining unit costs and creating a sound procedure for future unit cost updates in the model.

4. **Analysis of trigger criteria for crack seal application:** The use of crack sealing is prevalent throughout the state of Georgia. However, limited research has been done on when and where these treatments should be applied. This study aims to answer these questions using 15 years of historical segment-level condition

survey data on crack sealing within the state. The goal is to develop a framework for treatment analysis that is easily implemented by other departments of transportation.

5. **Development of applications and analyses to best support state-budgets:** By updating the model, this report aims to support more accurate state expenditure predictions for MR&R of asphalt pavements. Case studies to effectively convey the condition of the network of pavements maintained by the state and the budgetary need to achieve pavement performance goals will be conducted.

Major Findings and Developments

By implementing the changes discussed, the following results were presented:

1. **Model Development**

    a. An extensive literature review on pavement deterioration modeling revealed that while other methods may be adequate for modeling pavement deterioration, a Markovian approach is still recommended for use by the Georgia Department of Transportation. Previous research on Markovian models have supported the choice of these models for pavement deterioration modeling as they provide more accurate future predictions and make use of rich historical datasets.

    b. The use of state route priority categories to create pavement families resulted in the creation of 35 pavement families and subsequently 35 Markov Transition Probability Matrices (TPMs). The use of state route priority categories, working districts, and interstate versus non-interstate classification enabled better grouping of pavement projects with similar attributes and therefore, better modeling of pavement deterioration.

c. Through the introduction of more MR&R expenditure data, unit costs for major and minor preventative maintenance and major rehabilitation activities were determined. The resulting unit costs used in the model were $225,082, $2,577, and $316,321 per centerline mile respectively for non-interstates, and $885,605, $12,652, and $1,265,150 per centerline mile for interstates. The expenditure data was also used to determine the Annual Average Escalating Rates (AAER) of 1.79% per year.

2. Trigger Criteria Evaluation

a. A data processing procedure was put in place to remove segment-level data with missing information and duplicates. Using the methodology established, the number of raw segment-level entries was reduced from 562,648 to 455,342.

b. Through a preliminary study of crack sealing projects, the average Segment Rating before crack sealing was applied was found to be 69.75 within the state. The mean number of years in a row that crack sealing was observed in the survey was 2.087 years.

c. Using a difference in means between crack sealed and non-crack sealed projects, the Life 70 of a segment was found to be optimized when crack sealing was applied to segment with Segment Rating of 84.

3. Analyses to Support Decision Making

a. In a short-term analysis of pavement performance using the existing state budget of $448 million a year, Optimization on Each Family resulted in a composite rating of 81.50 after five years whereas optimization on the network resulted in composite rating of 84.05 at the end of five years. However, Optimization on Each Family resulted in an annual expenditure averaging $363 million rather than the full $448 million budget.

b. In a long-term analysis of pavement performance using the existing state budget of $448 million a year, Optimization on Each Family resulted in a composite rating of 80.73 after ten years whereas optimization on the network resulted in composite rating of 82.94 at the end of ten years. The average yearly expenditure for Optimization on Each Family was $357 million while Optimization on All Families utilized an average of $400 million a year.

c. A need analysis was conducted to determine the minimum funding necessary to achieve a composite rating of 85 for Critical interstate and non-interstate projects, a composite rating of 82 for High priority projects, a composite rating of 72 for Medium priority projects, and a composite score of 68 for Low priority projects. The average annual expenditure on

MR&R for the ten years of analysis was $134 million. However, the network composite rating fluctuates greatly over the analysis period; the network composite rating peaks at 94, but ends the ten-year analysis period with a composite rating of 77.3.

d. A second need analysis was conducted to determine the budget necessary to achieve the minimum suggested pavement condition under state law. The state requires a composite rating of 71 for both interstate and non-interstate routes. The analysis reported only $347 million was necessary per year over a ten-year period to achieve the federal requirements. However, the strategy does not represent a sustainable MR&R strategy.

e. A final need analysis was conducted using suggested state performance standards to define the budgetary need over a ten-year period. The suggested performance is focused on achieving a composite rating of 85 or greater with less than 10 percent of total pavements in the Poor or Bad condition category. For the first year of the analysis, $763 million was required to achieve the performance goals. However, subsequent years required significantly less investment on MR&R with an average budget of $351 million needed per year.

Future Recommendations

While the research conducted resulted in more up-to-date network-level modeling and decision-making strategies, additional research is recommended to further improve pavement management strategies. The following are suggested areas of improvement:

1. **Model Development**

    a. A more systematic means of processing and evaluating historical data is recommended. The creation of an application that automatically cleans and outputs COPACES data for the creation of Transition Probability Matrices is suggested.

    b. An evaluation of the usefulness of neural networks for pavement deterioration modeling should be studied more intensely. Through literature review, neural networks were found to be a viable tool for modeling pavement deterioration. A study of the usefulness of neural networks for COPACES data is recommended.

    c. An additional study on modeling cost escalation is recommended. While the existing model for cost used to support pavement preservation predictions is adequate given the data provided, a more dynamic means of predicting escalation would be more suitable for accuracy in modeling.

    d. Unit costs should be evaluated on a more granular level. In the existing model, unit costs were calculated for major and minor preventative maintenance and major rehabilitation. A closer look at individual pavement MR&R activities and the integration of additional treatment categories for each of the families created could result in better future predictions.

2. **Trigger Criteria Evaluation**

    a. To better support studies on pavement performance due to MR&R treatments, it is suggested that a policy be introduced to ensure additional treatments, besides crack sealing, are properly reported in the pavement condition survey. Doing so would enable additional studies on trigger criteria for MR&R treatments to be performed.

    b. To improve the data quality of crack sealing segment data, additional information should be collected during the pavement condition survey such as crack width and density. The collection of these additional variables would enable a more thorough analysis of the performance of crack sealing under varying conditions.

3. **Analyses to Support Decision Making**

    a. Additional features should be incorporated into the existing decision-making tool to enable more refined or poignant analyses about the budgetary needs of the state. Suggested additions include options to optimize based on state priority categories using both composite score and percent of pavements falling in the Poor and Bad state conditions.

b. Input from state legislators and policymakers is recommended to ensure the effectiveness of the created model and analysis tools. Input would ensure the models are adequately providing information that is easy to understand and utilize.

CHAPTER 1. INTRODUCTION

1.1 Background

As of 2017, Georgia Department of Transportation (GDOT) maintains and operates 17,902 centerline miles of interstate and state routes (GDOT, 2018). Despite the quantity of roadway mileage requiring maintenance, rehabilitation, and reconstruction each year, GDOT only received $402 million dollars from the motor fuel budget in Fiscal Year (FY) 2017 for routine maintenance (GDOT, 2018). The discrepancy between funds needed and funds available for maintenance is not unique; the problem is common for state departments of transportation (DOTs) throughout the United States. In order to mitigate the gap, careful planning and intelligent policies are required to maintain even minimum performance levels for roadways within the state.

To address the needs of GDOT, a Pavement Management System (PMS) has been implemented by Georgia. Pavement management systems, which have been widely adopted by state departments of transportations throughout the country, aid in decision-making related to when and where to apply treatments to pavements. While pavement management systems vary greatly from transportation agency to transportation agency, they usually consist of condition surveys, creation of pavement databases, creation of analysis schemes, formation of decision criteria, and finally, implementation (Peterson, 1987). These systems enable efficient decision-making and system optimization by providing cost-effective, long-term, network-level pavement management plans. Currently, Georgia's PMS draws upon historical pavement condition survey data from the Computerized Pavement Condition Evaluation System (COPACES) and tools implemented by the Office of Maintenance (OM) and the Office of Material and Research (OMR). While existing tools can predict funding required from the state for pavement maintenance and rehabilitation, the methods and tools in use today rely on data and cost estimates that predate FY 2010. With the availability of more current historical data and cost figures, the analysis of pavements maintained by Georgia can be more accurately predicted if updated. The sections to follow identify some of the needs and innovations required to upgrade the current PMS tools used. The aim is to create a more efficient and effective model for GDOT's PMS.

1.2 Research Need

In 2012, President Barack Obama signed into law the Moving Ahead for Progress in the 21st Century (MAP-21) Act to establish long-term highway authorization and spending programs specifically for surface transportation. The act was most notable for establishing performance-based programming and requiring states to invest in asset management. MAP-21 was the first piece of legislation requiring performance metrics and targets related to 1) pavement conditions on the interstate and National Highway System (NHS), 2) performance of the interstate system and NHS, 3) bridge condition on the NHS, 4) roadway safety on all roads, 5) traffic congestion, 6) on-road mobile source emission, and 7) freight movement on the interstate (§1203; 23 USC 150(c), 2012). The performance metrics and targets set are an important stipulation for a state to receive federal funding, especially after the passage of the Fixing America's Surface Transportation (FAST) Act in 2015. With the federal government's pressure to meet performance goals related to asset management, the updating of GDOT's existing PMS is crucial to achieve the goals set and to ensure federal funding for transportation is received by the state.

GDOT, which is responsible for a large network of primarily asphalt pavements, has been utilizing a model developed by Georgia Tech under Research Project 05-19 for its current performance analyses. While the model provides an adequate analysis of pavement performance within the network and adheres to both the MAP-21 and the FAST Act, the current model has not been updated in nearly 10 years. Because the existing model is a probabilistic model, the prediction power of the model suffers without the use of current data. Additionally, the GDOT has implemented a new policy that identifies the priority of pavement projects based on importance and utilization. The introduction of the new policy provides an opportunity to better categorize the current pavement system to maximize utilization of the GDOT's resources for maintenance. Advances in segment-level survey collection documentation also provides a potential area of improvement as the data enables Maintenance, Rehabilitation, and Reconstruction (MR&R) trigger criteria to be studied.

By utilizing new techniques, policies, and data, the existing model used by GDOT for the PMS can be improved. Questions about improved data processing, model development using pavement priority categories, and trigger criteria information can be answered by updating the previous model and utilizing the COPACES system. The results should be able to more efficiently and cost-effectively manage GDOT's pavement preservation planning at a network level.

1.3 Objectives

The overall objective of this research is to update and improve the existing PMS model utilized within Georgia. This report aims to thoroughly explain how the PMS is updated from data collection to implementation. By doing so, pavement performance analyses can be conducted in the statewide context. The objectives of the improvements made to GDOT's existing PMS model are as follows:

1) Redefine the historical data processing methods and grouping criteria for projects.
2) Study pavement deterioration behavior based on COPACES ratings and survey deduct values for different types of distresses.
3) Perform network-level analysis on pavement deterioration using newly defined pavement categories.
4) Explore historical data to summarize existing application timing for different MR&R treatments.
5) Perform a study to find the most suitable trigger criteria for MR&R treatments.
6) Perform network-level multi-year pavement performance-based and need-based analyses.

1.4 Report Organization

This report is organized into six chapters as summarized below:

1) **Chapter 1 Introduction**: This chapter introduces the project background, research needs, project objectives, and organization of the report.

2) **Chapter 2 Pavement Data Collection and Organization**: In this chapter, the history and current practices for pavement condition surveys and pavement project data collection and categorization in the United States and within Georgia are discussed.

3) **Chapter 3 Network-Level Study of Pavement Deterioration Behavior in Different State Route Priority Categories**: In this chapter, the current best practices used in pavement network-modeling are discussed. Additionally, an updated Markovian probabilistic model is proposed to simulate GDOT's long-term pavement maintenance needs. The proposed model uses historical data from the COPACES system, treatment unit costs, and the components of the existing model used for pavement preservation planning within the state.

4) **Chapter 4 Trigger Criteria for Maintenance and Rehabilitation Treatments**: The focus of this chapter is on the trigger criteria: when and what MR&R treatment should be applied for a given project. The chapter specifically takes a look at the segment-level analysis of crack sealing application and proposes the optimal timing for crack sealing application based on the segment-level data.

5) **Chapter 5 Analysis of Multi-Year Pavement Performance and MR&R Needs for State Funding**: Using the probabilistic model proposed in Chapter 3, this chapter focuses on analyzing pavements by forecasting their performance in both the short and long-term. In doing so, the MR&R needs will be predicted, and different analyses may be conducted. Important analyses include prediction of the network-level performance given a current funding level, or, given a performance goal, the funding required to maintain that performance level.

6) **Chapter 6 Conclusions and Recommendations**

7) **Appendices:** All supplementary documentation are included in Appendices A-E.

CHAPTER 2. PAVEMENT DATA COLLECTION AND ORGANIZATION

The Federal Highway-Aid Act of 1956 led the way for the construction of the federal highway system in place today. While the act provided federal dollars for the construction of the system, it was not until the Federal-Aid Highway Act of 1976 that the federal government took a larger role in the maintenance of the system created under President Eisenhower. The Federal Highway-Aid Act of 1976 provided a ninety percent federal share for “resurfacing, restoring, and rehabilitating” lanes in use for more than five years to reduce the $2.6 billion backlog of maintenance on the interstate system (Weingroff, 2017). While policy regarding federal and state funding for maintenance activities has changed throughout the course of history, the need to prioritize and program maintenance and rehabilitation activities that receive federal funding has remained constant. One key pavement management strategy that enables smarter prioritization and preservation of an entire network of pavements is the collection of pavement data for a PMS database and subsequent organization of pavement data to reveal useful trends for future prediction. Both pavement condition assessments and project categorization are important tools to standardize information about roadway projects and adequately assess which projects need treatments and when. The focus of this chapter is to 1) provide a brief history of pavement data collection and assessment in the United States and in Georgia and 2) describe how data collected for a pavement database can be organized to make meaningful predictions about a network of pavements.

2.1 Pavement Condition Data Collection

The collection of data by state departments of transportation is an important first step in the creation of a pavement management database. While details collected at a state level within the United States are largely dependent on the resources available to the state, data collection for pavement management is often focused on the collection of pavement condition data. In this section, pavement condition assessment metrics in the United States and in Georgia, specifically, will be discussed.

2.1.1 Condition Assessment and Data Collection in the United States

In the early days of the Interstate Highway System (IHS), pavement performance metrics were widely unexplored. It was not until 1961 in Ottawa, Illinois, that pavement conditions began to be systematically assessed to understand the performance of a network of roadways. In the early study conducted by the American Association of State Highway Officials (AASHO), the Pavement Serviceability Rating (PSR) was utilized to establish a condition score for pavements. The initial metric, which relied on a panel of expert raters who surveyed roadway segments by driving over them, laid the groundwork for more qualitative performance metrics used to analyze pavements today (HRB, 1961). This subsection looks at the three major pavement performance metrics that the PSR gave way to: the Present Serviceability Index (PSI), Pavement Condition Index (PCI), and International Roughness Index (IRI). The uses of these metrics for state-level pavement condition assessments are also discussed.

2.1.1.1 Present Serviceability Index

In 1962, the AASHO created the first and most generalizable rating system for pavement condition assessment. The metric created, known as the Present Serviceability Index (PSI), was formulated to indicate "the momentary ability of a pavement to serve traffic" (HRB, 1961). The rating was calculated using measurements of longitudinal profile variations and amounts of cracking, patching, and rutting. In 1993, PSI was altered to reflect the effects traffic and environment have on the performance of the pavement (AASHTO, 1993). The metric in its existing form measures the ability of a pavement to serve its users with a particular emphasis on roadway rideability or smoothness. PSI utilizes a 0-5 rating system, where 0 indicates a pavement with bad serviceability and 5 represents a pavement with high serviceability (Christopher, Schwartz, & Boudreau, 2006). Today, PSI is used for both flexible and rigid pavements and is a guiding metric for the design of new and rehabilitated roadway segments. Despite the generalizability of the metric, PSI lacks detail in terms of the types of distresses occurring on a segment or project level. Detailed information about distresses helps make informed treatment selections and, therefore, the PSI's lack of detail led to the creation of other pavement assessment metrics.

2.1.1.2 Pavement Condition Index

While the PSI is still used today, the reliability of the index as a metric, given the limited number of factors used in rating condition, has been often disputed. Therefore, a new metric has resulted: the Pavement Condition Index (PCI). PCI utilizes distress deducts for 1) alligator cracking, 2) bleeding, 3) block cracking, 4) bumps and sags, 5) corrugation, 6) depression, 7) edge cracking, 8) joint reflection cracking, 9) lane/shoulder drop-off, 10) longitudinal/transverse cracking, 11) patching and cut patching, 12) polished aggregate, 13) potholes, 14) railroad crossing, 15) rutting, 16) shoving, 17) slippage cracking, 18) swell, 19) raveling, and 20) weathering to characterize pavement condition (ASTM, 2011). PCI, which was developed by the Army Corps of Engineers, uses a 0-100 rating scale, where 0 represents a pavement in poor condition and 100 represents a pavement that is newly constructed or in the best condition. The index is calculated by deducting points from the highest possible score (100) based on the severity or extent of distresses. While PCI provides a thoroughness with the factors it considers, the process of determining PCI is limited by the resources needed to properly conduct the survey of all 20 distresses, making PCI not necessarily a feasible metric at a network level.

2.1.1.3 International Roughness Index

The International Roughness Index or IRI is a metric developed to understand pavement condition in terms rideability or roughness. The metric was developed in 1986 by the World Bank as a means to avoid empirical conversions between differing roughness indices around the world (M. W. Sayers, Gillespie, & Queiroz, 1986a). IRI is measured at a speed of 80 km/hour and is the accumulated suspension motion of a vehicle divided by the distance traveled (mm/km or in/mi) (M. Sayers, Gillespie, & Paterson, 1986b). Unlike PSI or PCI, IRI does not consider the structural integrity of the pavement, but focuses on the user experience on a roadway as does the PSR. Despite the lack of detail provided by IRI, the Federal Highway Administration (FHWA) mandated its use as a performance indicator on the National Highway System (NHS) to ensure acceptable ride quality. Today, FHWA pushes for IRI on NHS roads to be 170 inches/mile or less (FHWA, 2017a).

2.1.1.4 Current Pavement Condition Assessment Practices

Presently in the United States, pavement condition assessment metrics still vary considerably. While the measurement of IRI is required by states, most states use a combination of PSR, PCI, and IRI to assess network conditions. In a comprehensive study done by the University of Texas, it was found that 29 states collect distress information similar to PCI for assessment and 37 use IRI data for pavement rating (Papagiannakis, Gharaibeh, Weissmann, & Wimsatt, 2009). States, for the most part, were found to use the 0-100 rating of a Pavement Condition Index or 0-5 rating of a Pavement Serviceability Index with great variability in the sampling method and frequency of these surveys. Other state agencies, such as the Minnesota Department of Transportation, have created new indicators for condition assessment. The indicator used by the Minnesota Department of Transportation combines the concept of ride quality (similar to the IRI) with surface cracking and distress information (MNDOT, 2011).

2.1.2 Pavement Condition Assessment and Data Collection in Georgia

In 1986, the Georgia Department of Transportation implemented the use of the Pavement Condition Evaluation System (PACES), which utilizes distress surveys and empirical data to rate pavement throughout the state (GDOT, 2007). The PACES, which uses distress deduct values to calculate a pavement rating between 0 and 100, represents a balance between the simplicity of PSI and the thoroughness of PCI. The system, which has been utilized for yearly pavement surveys, has remained consistent for the nearly thirty years it has been in use. The sections below give an overview of the details of the collection method for condition assessment data used by PACES and other data provided by the Computerized PACES (COPACES).

2.1.2.1 Condition Collection Methods

As described previously, the main data source for pavement condition of projects within within the state is COPACES. The data in the system includes project-level and segment-level information about all interstate and state routes dating back to FY 1986. Just as in other rating systems, visual surveys are a vital aspect of determining the rating of the pavement as well as the overall condition of the state. Because visual inspections are both time consuming and labor intensive, the Georgia Department of Transportation (GDOT) conducts surveys for each mile of roadway by "selecting a sample section for cracking distresses representative of the pavement condition for that rating segment" (GDOT, 2007). These mile selections are considered "segments," and the representative 100-foot samples are referred to as sections. The ratings of segments are averaged together to obtain a representative pavement condition for an entire project. Projects are, typically, lengths of roadway with common pavement features (such as mix design, year reconstructed, etc.) and logical termini. Therefore, survey data often includes variability as the representative section chosen may vary from year to year.

Figure 1 provides an illustration to help distill the relationship between sections, segments, and projects.

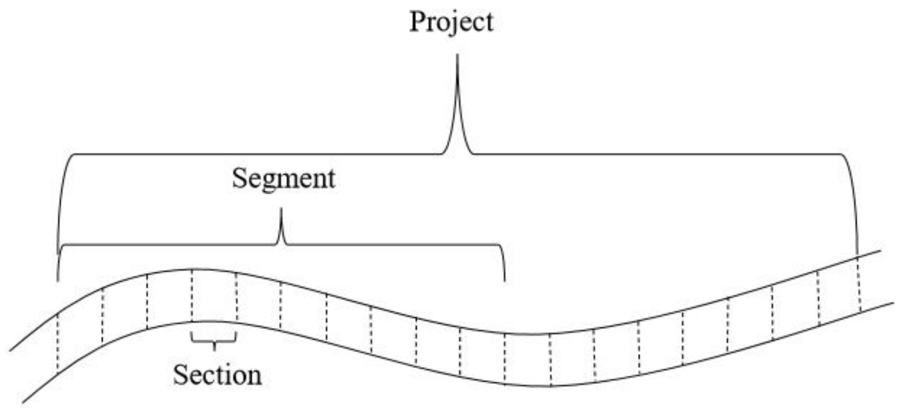

Figure 1. PACES survey sampling terminology

The ratings procured during section surveys consider ten distresses of varying degrees. Distresses include rut depth, raveling (Levels 1-3), load cracking (Levels 1-4), edge distress (Levels 1-3), block cracking (Levels 1-3), bleeding/flushing (Levels 1-2), reflection cracking (Levels 1-3), corrugations/pushing (Levels 1-3), patched and potholes, and loss of section (Levels 1-3). The rater chooses the worst lane in a multilane section where divided highways are treated as separate sections. **Table 1** provides a summary of the characteristics needed to rate each distress, whereas Appendix A summarizes how these characteristics are used to determine distress deduct values. Ultimately, all of the deduct values from segments that fall within a project are averaged together to get project-level deduct values.

Table 1. PACES distress information

Distress Type	Description of Measurement
Rutting	Pavement distance from flush grade on wheel paths (inches)
Raveling	Percentage of sample area with predominant raveling level observed (%)
Load cracking	Percentage of sample area with highest level of cracking observed (%)
Edge distress	Length of edge with predominant severity level (mile)
Block cracking	Percentage of sample area with highest level of cracking observed (%)
Bleeding/Flushing	Percentage of length of wheel paths that has bleeding or flushing in a segment (%)
Reflection cracking	Percentage of sample area with highest level of cracking observed (%)
Corrugations/pushing	Percentage of rated segment that has corrugations (%)
Patched and potholes	Number of spots for the entire rated segment
Loss of Section	Percentage of length of rated segment with loss of pavement section (%)

The deduct values calculated per project or segment are important, as they are ultimately used to summarize pavement condition. Pavement condition can be summarized by a Project Rating number that varies from 0-100. A Project Rating of 100 represents pavement with no visible distresses, whereas a Project Rating of 0 represents the worst condition a pavement can be in. Additionally, projects with a Project Rating of 105 are projects considered to be under construction. GDOT utilizes these ratings to analyze the system at the network level.

2.1.2.2 Other Information Collected in the COPACES

Historical COPACES data since FY 1986 is used to describe the trend in pavement condition deterioration for projects over time. As stated previously, COPACES data includes segment and project-level condition data, as well as distress information. However, the large data set that has been used for Georgia's Pavement Management System (PMS) also includes fields such as district location, status of the project (if under construction), whether a project is on a divided highway, and other fields listed in Appendix B. These additional attributes help identify key characteristics of projects assessed during surveys.

2.2 Other Data Sources for Pavement Management Databases

In order to validate and calibrate deterioration models to fully understand condition trends for pavements, multiple data sources are required. Besides condition assessment data, two of the main data sources needed to fully understand a state's network of pavements are historical traffic data and treatment expenditure data. Below, each source is more thoroughly described in the context of the Georgia Asset Management System (GAMS).

2.2.1 Historical Traffic Data

Since the AASHO Road Test, conducted in the late 1950s and early 1960s, the effect of volume and mix of traffic on pavement deterioration has been incorporated in pavement modeling techniques. In a study by Alberto Garcia-Diaz et al. (1984), the nonlinear relationship between pavement condition and traffic loading was confirmed. The study, which utilized test data from the Texas Department of Transportation, found that the relationship between pavement condition (PSI) and traffic (Equivalent Single Axel Loads (ESALs)) was sigmoidal in nature or that pavement conditions increasingly worsen with an increase in traffic loading (Garcia-Diaz & Riggins, 1984). Traffic data, in the form of Annual Average Daily Traffic (AADT), is, therefore, an important source for understanding and predicting future pavement condition, especially when categorizing pavement projects at a network level. Traffic data at a state level is provided by PACES data, as well as the GDOT's Geocounts system that provides all annual traffic data from the state's permanent counter locations.

2.2.2 Treatment Expenditure Data

While treatment expenditure data does not play a great role in understanding existing pavement conditions within a state, these data are important in the context of general pavement management and expenditure forecasting. While the cost of materials and labor fluctuates each year due to inflation and industry demands, a predicted cost for future years can be deduced from a state's historical expenditure data. The data provided by Georgia's GeoPI system, which contains resurfacing information, and the Work Order system, which contains expenditure data for preventative maintenance, is sufficient for the prediction of treatment and rehabilitation costs within the state.

2.3 Organization of Network-Level Pavement Data

The collection of pavement condition, traffic, and expenditure data provides little value on its own. In order to thoroughly draw conclusions about pavement conditions within a network, the data must be properly organized in a way that enables conclusions to be drawn based on characteristics of pavement projects. At the network level, the Georgia Department of Transportation does this by using Project Ratings. The Project Ratings gathered from COPACES data describe the five key conditions of pavement: Excellent, Good, Fair, Poor, and Bad. These condition states are used to indicate how a pavement is performing based on the distresses found through the survey process. The condition states and the associated ranges of Project Ratings for each are summarized below in **Table 2.**

Table 2. Project Rating categories

Category Name	Project Rating Range
Excellent	91-100
Good	81-90
Fair	71-80
Poor	55-70
Bad	0-54

These pavement condition categories enable the DOT to easily identify the existing conditions of the asphalt pavements operated and maintained by GDOT. For example, using processed 2015 PACES data, a breakdown of the pavement condition in the state can be easily understood using these categories. The composite rating of the network of pavements, where the composite rating is defined as the summation of all the Project Ratings multiplied by their respective project lengths and divided by the total mileage of the network, was 79.57 out of 100.

Figure 2 represents the distribution of the pavements in the network for FY 2015 using state condition categories. From this figure, it can easily be distilled that less than 50% of pavements in Fiscal Year 2015 were in the "Good" or "Excellent" category, while the more than half of pavements in the network ultimately require some form of minor treatment or major rehabilitation.

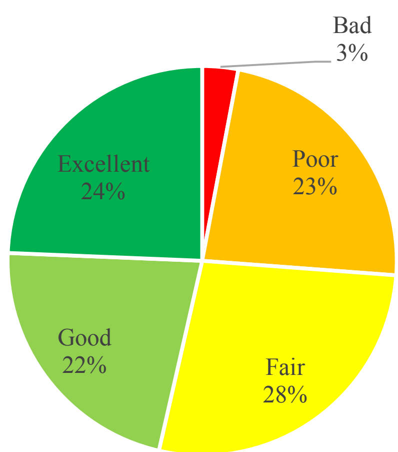

Figure 2. State of network of pavements in Georgia, FY 2015

While information about pavement condition states is a great tool for communicating pavement performance at the state level to policy-makers and, subsequently, setting performance goals, little can be gathered about the condition states of highly valued or highly utilized roadways versus underutilized roadways using these categories alone. At the network level, state-wide pavement condition states are often difficult to understand for decision-making regarding where to invest in maintenance and rehabilitation given the variability in pavement rating, pavement location, and other attributes of a project that affect pavement deterioration. When comparing projects, these additional factors play a large role in how fast and how detrimental deterioration of the asset will be. Therefore, project organization beyond condition states is necessary to adequately understand future and existing conditions of the system and subsequent action that needs to be taken. By organizing projects by criteria other than Project Rating, the goal is to enable condition assessment to be more holistic, and, therefore, comprehensive in terms of understanding how pavement groups work.

Within Georgia, three additional categories are imposed to group similar pavement projects, two used in the previous studies on pavement management in Georgia and one recently defined and implemented in the state. The preexisting means of classifying roadway projects is by using the working district in which a project falls and through the project's classification as interstate versus non-interstate. The additional classification criteria imposed for data organization is state prioritization. Each of the three components used for grouping similar projects is described in the subsections below.

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2.3.1 Working District

In Georgia, there are seven working districts as determined by the Georgia Department of Transportation. These seven administrative areas encompass regions that share resources from the GDOT District offices. The boundaries correspond to county boundaries which generally remain consistent from year to year as seen in

Figure 3.

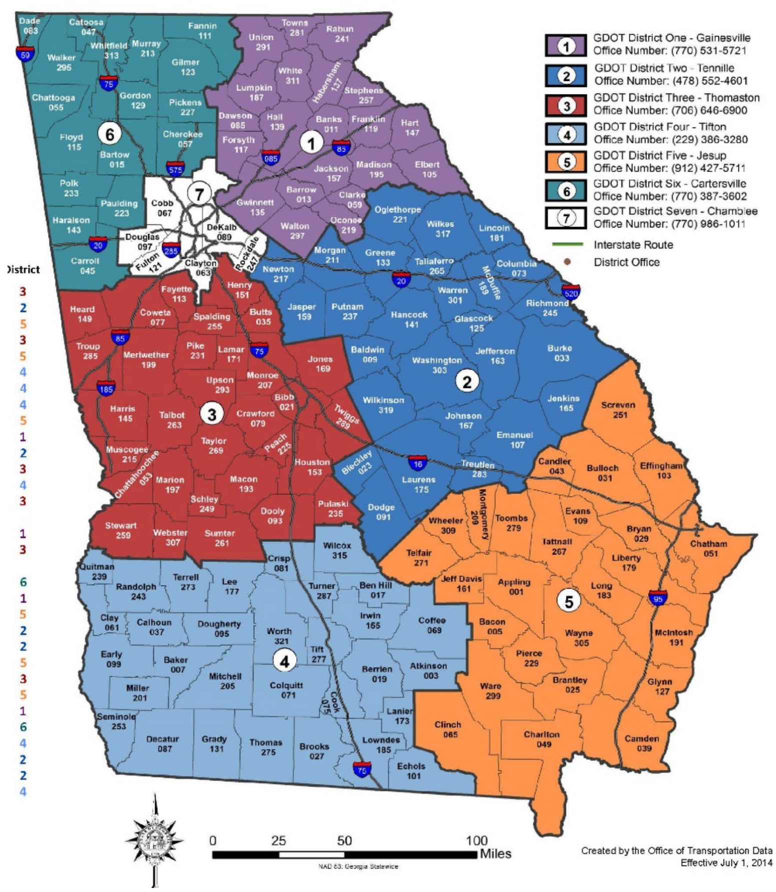

Figure 3. GDOT Working Districts (GDOT, 2014b)

The use of the working district of a project as a geographical category enables projects with similar weather and soil conditions to be grouped together. In Georgia, this is particularly important, as the state's geography varies greatly above and below the Fall Line depicted as Sand Hills in

Figure 4 below. The elevations tend to be greater and the soils tend be classified as clays above the Fall Line. Below the Fall Line, the elevations tend to be less and the soils tend to be classified as sands. While working districts do no capture the geographic differences between projects perfectly, they provide a good basis for differentiating pavements by location.

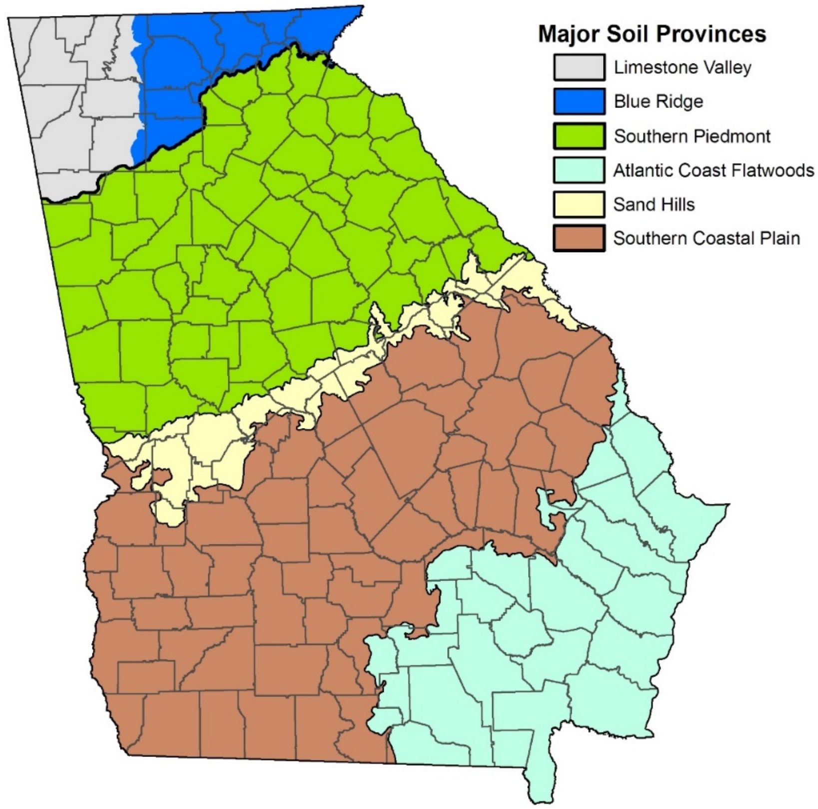

Figure 4. Soil differences in the state of Georgia (UGA, 2017)

2.3.2 Interstate versus Non-Interstate

Another category used to classify projects is the whether the pavement is an interstate or a non-interstate roadway. An interstate roadway is any roadway that is a part of the National Highway System and, therefore, serves as a major corridor for freight and connectivity within the state. In Georgia, interstate roadways are all denoted by a state route number in the 400s such as SR 404 (I-16), SR 402 (I-20), and SR 409 (I-24). As of 2014, only approximately 1,247 centerline miles can be classified as interstates within the state (GDOT, 2014a). Non-interstate roadways are those that are not necessarily a part of the NHS, but are still maintained and operated by the state; in Georgia, such roadways are approximately fifteen times the centerline mileage of interstates. Splitting projects between these two road types helps account for differences in traffic, loading due to truck percentage, and pavement design type, which often varies greatly between interstate and non-interstate pavements.

Figure 5 shows interstate and non-interstate roadways in Georgia.

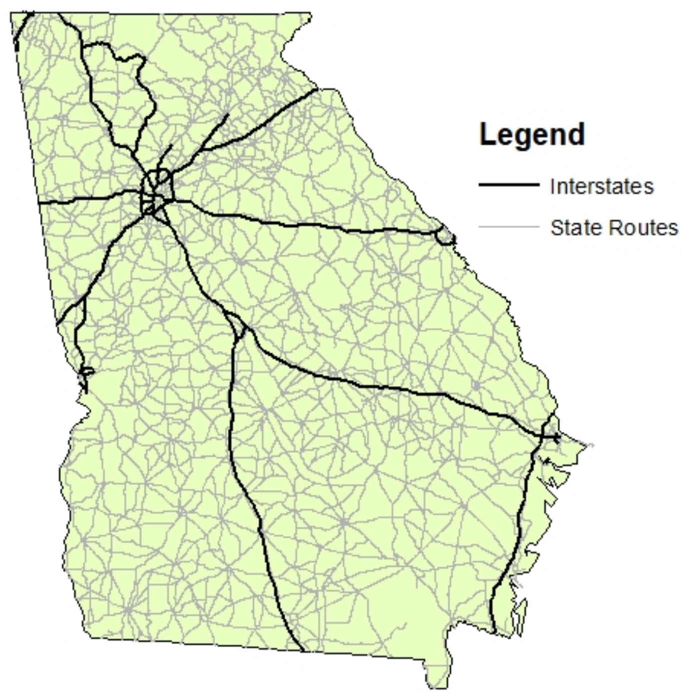

Figure 5. Interstate versus non-interstate mileage in Georgia

2.3.3 State Prioritization

The final means of organizing pavement project data is through the use of state prioritization. In 2015, Wiegand et al. (2016) created a new means of categorizing roadways for maintenance prioritization and better performance measures. Four categories were created based on the importance of roadways for connectivity and access, as detailed in **Table 3** (Wiegand & Susten, 2016). The four categories (Critical, High, Medium, and Low) can be used to further group projects based on their importance in the pavement network.

Figure 6 depicts the classification of state route priority throughout the state roadway network.

Table 3. Characteristics of state route priority categories (Wiegand & Susten, 2016)

Category	Characteristics of Roadways
Critical	• National Freight Corridors • State Freight Corridors • Interstates • Intermodal Connectors
High	• STRAHNET/STRAHNET Connectors • NHS-Other Principal Arterials [Annual AADT>3000] • U.S. Routes • Sole Connections between County Seats • Georgia Emergency Management Agency Nuclear Power Plant Evacuation Routes
Medium	• Hurricane Evacuation Routes • NHS – Other Principal Arterial Routes Beginning or Ending at a Low Priority State Route • NHS- Other Principal Arterials (AADT <3,000) • All Other Routes that not otherwise classified
Low	• Low AADT (Under 3,000) • Low Speed Limit (Under 35 mph) • Low Connectivity (i.e. spans a single county, does not connect an urban area) • Short Length (Total Mileage<5 miles) that are not otherwise classified

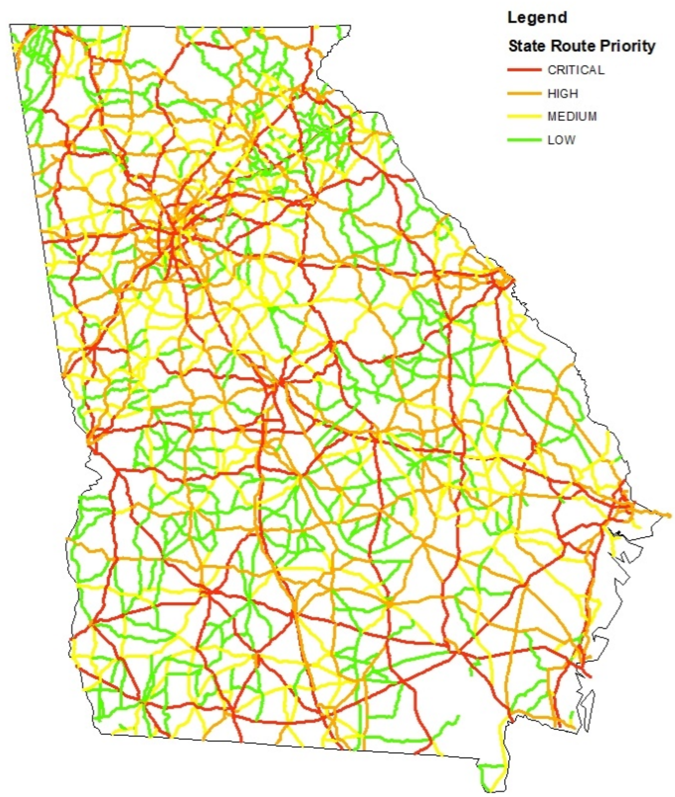

Figure 6. State route prioritization categories

CHAPTER 3. NETWORK-LEVEL STUDY OF PAVEMENT DETERIORATION BEHAVIOR IN DIFFERENT STATE PRIORITY CATEGORIES

To create a rigorous Pavement Management System, the data collected and stored by Georgia Department of Transportation should be used to create a model focused on predicting pavement deterioration and therefore, the need for Maintenance, Rehabilitation, and Reconstruction activities in the future. Proper prediction of pavement deterioration and network-level need requires detailed data sources, the right type of prediction model, and proper assumptions about the network considered. In this chapter, pavement deterioration modeling generally and for GDOT will be considered. In the subsections that follow, an introduction of existing pavement performance models utilized by pavement engineers will be summarized, and the selection and updating of a Markovian probabilistic model for Georgia will be described.

3.1 Pavement Deterioration Modeling

Pavement performance deterioration has been studied since the AASHO Road Test in the early 1960s. With advancements in computation speed and roadway data collection techniques, the study of pavement deterioration has also advanced. While new methods for understanding pavement performance over time are continuously being developed, the types of modeling used, especially within the United States, can largely be categorized into deterministic models or stochastic models. Deterministic modeling, which includes mechanistic models, empirical models, and mechanistic-empirical models, utilizes parameters or inputs that include no randomness and therefore result in stationary outputs. Stochastic or probabilistic modeling, conversely, utilizes random variables to estimate how probable outcomes may be in prediction. Examples of stochastic or probabilistic models include econometric, Markov Chain, and reliability models (Z. Li, 2005). In the following sections, the use of deterministic modeling and probabilistic modeling for pavement performance is discussed.

3.1.1 Deterministic Modeling

As stated previously, the focus of deterministic models is to predict a precise or constant future value based on input values. In the context of pavement performance, this can mean that a series of pavement performance indicators for a network are used to predict the exact performance of the pavement network in future years. Deterministic modeling, is therefore commonly used by state departments of transportation as it is utilizes data already collected through condition assessments and is easily explained to decision-makers. However, these models do fall short in being able to comprehensively account for all the variables and randomness of variables affecting pavement condition or performance. The focus of this section is to more fully describe the use of deterministic modeling in the realm of pavement performance. Three subsets of deterministic models most often used by these entities are mechanistic modeling, empirical modeling, and mechanistic-empirical modeling. The use of each model type in the context of pavement deterioration modeling are described below.

3.1.1.1 Mechanistic Models

Mechanistic models utilize mathematics and physics to evaluate a pavement's response. For pavements, mechanistic models are those that consider stress, strain, and deflection to better understand pavement structure (Rauhut, Lytton, & Darter, 1982). While mechanistic models are commonly used in pavement design such as the models developed by Ontario, Canada's OPAC software (He, 1997), use of mechanistic models for modeling deterioration or performance has been scarcely studied. Hajek et. al. (1985) studied the difference in multiple performance models including a mechanistic model utilizing the OPAC design formulas. By utilizing the relationship between deflection of subgrade and pavement roughness, the mechanistic model was able to adequately predict the PCI of a pavement over time. However, the mechanistic model was considered an overprediction of the actual PCI data collected in the state of Mississippi in this study (Hajek, Phang, Prakash, & Wrong, 1985). In addition to overprediction, mechanistic models are also limited by the factors they are able to model, the precision of the modeling, and the need to calibrate each model used usually with empirical data (AASHTO, 1993).

3.1.1.2 Empirical Models

Empirical performance models are widely used for the identification of pavement performance trends through the use of experimental data. Unlike mechanistic modeling, which often relies on lab tests, empirical modeling can make use of survey data and other easily collected parameters to predict performance over time. For that reason, empirical modeling has been used to understand the dependencies of ESALs (Garcia-Diaz &

Riggins, 1984; HRB, 1961), roughness (Al-Omari & Darter, 1994; Lin, Yau, & Hsiao, 2003), and varying distresses on pavement performance. Empirical modeling for pavement deterioration has taken both linear and non-linear forms such as sigmoidal models (Chen & Mastin, 2015) and survivor curves. However, despite the practicality of using empirical data for prediction of pavement performance using condition or age, it is more common for state DOTs or research entities to use a combination of mechanistic and empirical data.

3.1.1.3 Mechanistic-Empirical Models

Mechanistic-empirical models incorporate both mechanistic data collected about material properties and empirical data collected through field evaluations. Most PMS utilizing mechanistic-empirical models focus on pavement serviceability through the use a combination of variables such as traffic loads, environmental factors, materials, subgrade strength, construction technique, and layer thickness (George, Frajagopal, & Lim, 1989). In some cases, these factors are incorporated into the model directly, while for others, pavements are first grouped into like families based on similar characteristics such structure, last resurfacing, and traffic volumes before a model is developed (Chan, Opperman, & Wu, 1997). The modeling is focused on combining these factors to best understand the characteristics of pavements through methods such as regression (Chan et al., 1997), stepwise regression (Shahin, Nunez, Broten, Carpenter, & Sameh, 1987), multiple linear regression (Luo, 2014), and reliability models (Alsherri & George, 1988) among others. While mechanistic-empirical models are widely used due to their ability to consider a breadth of factors affecting pavement condition, these models are still limited by their inability to account for errors deterministic models create by utilizing fixed inputs in the model.

3.1.2 Stochastic Modeling

Stochastic or probabilistic modeling utilizes non-discrete measures for prediction. Non-discrete measures can include random variables and probability distributions of variables and outcomes that encapsulate the randomness of an event such as pavement deterioration occurring. As alluded to previously, stochastic modeling often takes the form of econometric, Markov Chain, and reliability models; however, in pavement management, Markov Chain is predominantly used. Despite the benefits of considering pavement data in a dynamic lens, probabilistic models are considerably more complex and therefore, have only been used more recently as computation speeds have increased. The subsections to follow provide an overview of Markov Chain in the context of network modeling as well as other new probabilistic techniques being use by researchers and state DOTs.

3.1.2.1 Markov Chain Models

Markov probabilistic modeling has been utilized for PMS since its introduction into the field by the Arizona DOT in 1982 (Golabi, Kulkarni, & Way, 1982). This stochastic or probabilistic model type utilizes historical data to predict the likelihood of a pavement deteriorating from one condition to the next. Markov models assume that all future states of a system depend only on the current state of conditions rather than events that occurred in the past as stated by the Markov property. However, the definition of a condition state and the likelihood of state changes differ for homogenous and nonhomogeneous Markov models.

Homogenous Markov modeling refers to Markov models that assume that transition probabilities of condition states are constant or stationary over time. In the context of pavement management, homogenous models would assume that the likelihood of a pavement deteriorating from one condition to another each year would remain the constant. For example, if pavement can be divided into two condition states, good and failing, then for a homogenous Markov model, the assumption is that the probability of a pavement in the good category transitioning to the failing category would be the same from year to year. The Markov method was first deployed by the Arizona DOT which utilized 120 condition states based on roughness, amount of cracking, change in cracking in previous years, and index to the first crack and 17 maintenance activities to create transition probability matrices for network deterioration prediction (Golabi et al., 1982). Butt et al. (1987) utilized a similar integration of homogenous modeling for a pavement network focused on 10 states of PCI and no maintenance activities which provided better predictions of future conditions than a comparable least-squares model. In Butt's model, given no maintenance events were considered, the transition probability matrices (TPMs) for each family assumed a pavement could not improve its condition. Other studies have further refined models similar to ADOT's proposed in 1982 by assuming pavements can only deteriorate one condition per analysis period (Wang, Zaniewski, & Way, 1994) and further refining pavement "families" selection (N. Li, Xie, & Haas, 1996).

Nonhomogeneous Markov models do not assume or have supporting evidence that TPMs will be stationary over time. Therefore, nonhomogeneous models can be considered non-stationary. Typically, these models are created using time-based or state-based models. The former focuses on the time taken for a pavement to deteriorate from one condition to another while the latter considers probabilities over a defined time period (Mishalani & Madanat, 2002). Non-homogenous state-based models include expected-value method, simulation methods, and econometric methods while timed-based models include parametric, semi-parametric, and non-parametric duration models (N. Li et al., 1996). These advance methods have been researched and implemented in recent years through the use of Poisson Hidden Markov models (Lethanh, Kaito, & Kobayashi, 2015) and Bayesian updating of Markov models (Hong & Prozzi, 2006; Tabatabaee & Ziyadi, 2013).

Markovian models are best used by states or agencies with unreliable or small historical datasets as these methods can predict future performance given a finite amount of data. Therefore, using Markov processes requires less data collection and resources than some of the empirical and mechanistic methods of modeling previously described. The data used to create a Markov model, while beneficial in terms of expenditure on data collection, means the model does not consider the causes of pavement deterioration directly. Therefore, Markov models are not appropriate for decision-making at a project level.

3.1.3 Other Modeling Techniques

Other modeling techniques discussed in pavement management literature include neural networks. Neural networks were introduced as computing systems advanced and machine learning was introduced into the pavement management field. These systems, which consist of input values or neurons, hidden layers, and outputs, utilize collected data to output a network condition. In neural networks, inputs typically include factors that would be considered by deterministic modeling including roughness, pavement age, climatic conditions, pavement structural properties, subgrade properties, drainage type, and MR&R treatments (Kargah-Ostadi & Stoffels, 2015). The use of neural networks when compared to empirical or probabilistic methods alone are mixed. Karagh-Ostadi et al. (2015) determined Bayesian Neural Networks resulted in good accuracy and generalization when compared other machine learning techniques, and Lou et al. (2001) similarly found use of neural networks resulted better accuracy (lower error) than a comparable autoregressive model. Luo et al. (2014), however, found that use of neural networks lead to higher levels of variability than the use of solely multiple linear regression models for pavement deterioration. Additionally, the forecasting error associated with neural networks was shown to increase more quickly with the number of years in the future needed to be predicted when compared to a Markov model (Yang, Lu, Gunaratne, & Dietrich, 2006). This suggests that neural networks may not be appropriate for long-term pavement preservation planning.

3.2 Development of a Network-Level PMS Model for Georgia

Based on the literature review conducted and an analysis of the function of the existing PMS model used by the GDOT and developed by Georgia Tech, the continued use of a Markovian-based model for the GDOT's PMS seemed to be the best choice for understanding pavement deterioration within the state. While the existing model developed under Research Project 05-19 has proven to be adequate for high-level management, the model needed to be updated using the most current data about state network conditions in order to meet the needs of the GDOT.

In this section, the full procedure for updating the existing probabilistic model used by the Georgia Department of Transportation is described. This includes the data processing procedure for network-level data, the pavement families created for better studying pavement deterioration, the newly updated Markovian Transition Probability Matrices (TPMs) based on current COPACES data, the updated expenditure data required to accurately predict pavement MR&R costs, and finally a summary of how the existing model uses these updated components to create expenditure and condition predictions.

3.2.1 Data Description

As discussed in Chapter 2, one of the main sources of data at a network level is COPACES data. The data provided by the database enables a closer look at the geographical location of projects and Project Ratings for the entire state network. For the purpose of this study, project information was primary source of data used to understand the Georgia pavement network. Project location information was used to identify trends in pavement deterioration over time, and Project Ratings were used as the metric for deterioration. While the COPACES system contains data from FY 1986 to present, due to the nature of the model chosen which more accurately predicts pavement deterioration using the most recent data available, only the most recent five years of data available were used to update the PMS model. Therefore, information about the network was limited to FY 2010- FY 2015 for the purpose of the study. Despite limiting the data to a five-year period, the volume of data and the need to further process the data remained. Section 3.2.2 describes in detail the procedure for assuring data veracity.

3.2.2 Data Processing

While the process of data collection and surveying by the GDOT is done by trained personnel, the quality of data in the COPACES remains variable. For the most part, errors in the system result from differences in rater opinions as well as data entry errors. While these issues can be minimized through training and safe locks on the data collection entry tools, the errors cannot be completely eliminated. Therefore, the importance of processing data, even at a network level, is crucial to maintain data veracity.

The COPACES condition survey projects from 2010 to 2015 were processed for the purposes of model development. The following are the steps used to process the data at a network level:

1. Filter out the projects with missing critical information, such as Project Rating.

2. Filter out the projects that are not surveyed by AO which represents projects surveyed at a local level rather than a district or state level for consistency in the data used.

3. Filter out the non-asphalt surface type projects.

4. Eliminate the projects with under-construction status.

5. Assign each project a Project ID. Project IDs are created by concatenating the County Code, Route Type, Route Number, and Route Suffix (known collectively as an RCLink) with the milepost to and from fields for each project. Filter out the duplicated projects.

6. Eliminate the projects with irrational deterioration trend such as when a Project Rating is improved without rehabilitation for a particular Project ID.

Appendix C provides a more in-depth explanation of some of these processes. Overall, these steps improve the quality of data for further analysis at a network level.

3.2.3 Pavement Families

Following data processing, data was grouped to create more concise and related pavement "families" as is discussed in Chapter 2. In the previous model, 14 pavement families were developed. The families were created using the seven working districts and interstate and non-interstate distinction. While the results of these groupings were adequate, additional information about pavement projects was used to further group the projects and create new project families. In the updated model, 35 pavement families were created. These 35 families were created based on the seven working districts, interstate versus non-interstate distinction, and finally the state route priority category.

Figure 7 more clearly depicts the division of the pavement projects into families with a detailed look of the division of projects in District 1.

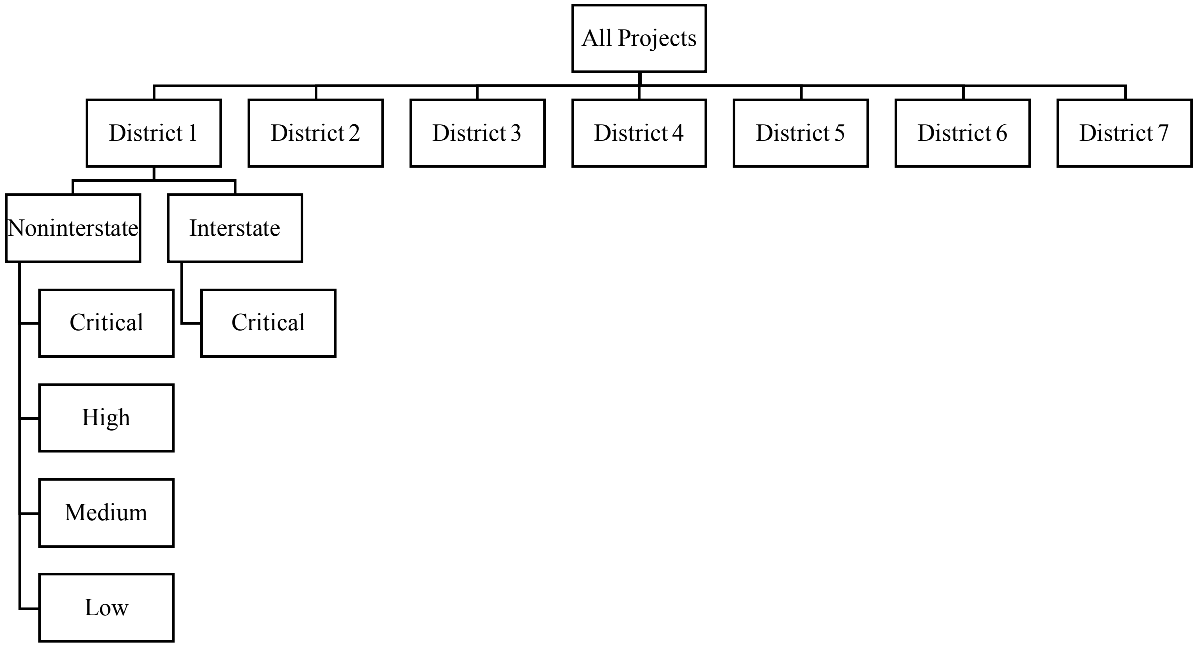

Figure 7. Pavement family example for updated model

3.2.4 Pavement States

As discussed in Chapter 2, the Georgia Department of Transportation currently uses five condition states to describe pavement. The conditions states include "Excellent", "Good", "Fair", "Poor", and "Bad." These conditions are used to define homogenous Markovian states and to create subsequent Transition Probability Matrices. **Table 4** and

Table 5 provide an overview of the condition states of non-interstates and interstates within the GDOT system between FY 2010 and FY 2015.

Table 4. Non-interstate highway pavement condition from FY 2010-FY 2015

Year	Bad	Poor	Fair	Good	Excellent	Composite Rating
2010	1.86%	23.13%	26.71%	19.02%	29.28%	80.81
2011	2.57%	24.98%	26.65%	18.82%	26.98%	79.90
2012	2.83%	26.40%	28.51%	18.12%	24.14%	78.93
2013	3.26%	27.97%	26.88%	18.69%	23.19%	78.37
2014	3.68%	24.90%	25.92%	21.11%	24.40%	79.12
2015	3.18%	24.03%	27.84%	22.14%	22.80%	79.09

Table 5. Interstate highway pavement condition from FY 2010-FY 2015

Year	Bad	Poor	Fair	Good	Excellent	Composite Rating
2010	0.98%	17.76%	15.16%	24.02%	42.08%	85.22
2011	1.16%	16.96%	22.15%	15.28%	44.44%	84.30
2012	3.72%	11.07%	30.27%	17.02%	37.93%	83.92
2013	1.96%	6.68%	30.97%	15.46%	44.94%	86.54
2014	0.47%	21.29%	21.21%	12.97%	44.05%	84.25
2015	0.03%	11.34%	20.71%	20.99%	46.92%	86.44

3.2.5 Markov TPMs

The Markov TPMs for each family depict the pavement deterioration trends for each group. The TPMs created represent the probability of a pavement deteriorating from one condition to the next over a year's span. The probability of a pavement's state change is represented by p_{ij} where i is the condition of the pavement in the first year and j represents the condition of the pavement in the second year. **Table 6** depicts the general notation for a Markov TPM. As described by the table, it is assumed that a pavement can 1) only deteriorate (cannot improve) over the span of a year without treatment and 2) pavements are constrained to deteriorating to the next lowest condition state over the span of a year. These assumptions are supported by both previous literature and engineering judgment.

Table 6. Notation of Markov TPM

States j i	Excellent	Good	Fair	Poor	Bad
Excellent	p_{11}	p_{12}	0	0	0
Good	0	p_{22}	p_{23}	0	0
Fair	0	0	p_{33}	p_{34}	0
Poor	0	0	0	p_{44}	p_{45}
Bad	0	0	0	0	*1.0*

For the purpose of this analysis, p_{ij} is the percent of all pavements in a family that have deteriorated from condition state i to condition state j over the one-year analysis period. This calculation is computed using historical data in each family. To calculate the probability of p_{ij}, the sum of all the mileage of pavements that transition from state i to state j in a year's time is divided by all the total mileage of pavements within a family that were of condition state i at the start of the analysis. Using the general notation and definition described, the matrices follow three rules:

1. The probability p_{ij} should be a number between 0 and 1.

2. The sum of p_{ii} and p_{ij} should be equal to 1.
3. All other items in the matrix should be equal to 0.

As alluded to previously, one TPM was created for each of the 35 families specified to account for differences in deterioration that may occur in like groups. TPMs were created using historical COPACES survey data from FY 2010-2015 that were processed and cleaned as described in Section 3.2.2. In instances where pavements did not adhere to the assumption of only one condition state drop per year, pavement projects were not considered in the creation of TPMs. However, the amount of projects dropping more than one condition state in a year was less than five percent of total mileage in the group analyzed. Additionally, adjustments had to be made for all families' transition probabilities from Fair to Fair, Fair to Poor, Poor to Poor, and Poor to Bad. Due to the low number of mileage used to calculate these probabilities for each of the families initially, the same probability was used for each family for the described transitions. A probability of 0.5, 0.5, 0.9, and 0.1 was used for the transition from Fair to Fair, Fair to Poor, Poor to Poor, and Poor to Bad respectively. These probabilities were chosen as they minimized the difference between the model results and historical results for expenditure discussed in the Section 3.2.8.

Table 7 shows an example of the TPMs created for the Critical, Non-interstate families for all seven working districts. TPMs for all families are included in Appendix D.

Table 7. TPMs for Critical, Non-interstate families for 7 Working Districts

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7034	0.2966	0	0	0
Good	0	0.5501	0.4499	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 2					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7867	0.2133	0	0	0
Good	0	0.8082	0.1918	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 3					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.6704	0.3296	0	0	0
Good	0	0.7318	0.2682	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 4					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.8225	0.1775	0	0	0
Good	0	0.7008	0.2992	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 5					

	Excellent	Good	Fair	Poor	Bad
Excellent	0.7821	0.2179	0	0	0
Good	0	0.7046	0.2954	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 6					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.5995	0.4005	0	0	0
Good	0	0.6834	0.3166	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 7					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.4161	0.5839	0	0	0
Good	0	1	0	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1

3.2.6 Treatments and Performance

Following the development of the Markov TPMs, MR&R activities must be defined and incorporated into the prediction model so that future costs can be estimated based on predicted network-level performance. Since detailed information on expenditure of specific MR&R activities is not easily obtained due to lack of integration of pavement management tools under the state's current system, three treatment categories were defined for the purpose of this model: Minor Preventative Maintenance, Major Preventative Maintenance, and Major Rehabilitation/Reconstruction. These MR&R categories are used as associated treatments for varying pavement conditions within the model. An overview of when these activities are to be applied is depicted in

Table 8.

Table 8. Treatment for corresponding condition states

State	MR&R Activities
Excellent	Do Nothing
Good	Do Nothing
Fair	Do Nothing, Minor Preventative Maintenance
Poor	Do Nothing, Major Preventative Maintenance
Bad	Do Nothing, Major Rehab/Reconstruction

Using the above decision criteria for treatment application in the model, the unit costs for each treatment type had to be calculated as well as the Annual Average Escalating Rate (AAER) for all treatments in order to properly track increases in the unit costs over time. The subsections to follow describe the procedure for calculating the unit costs and AAER necessary for the model.

3.2.6.1 Unit Cost Calculations

Unit costs had to be calculated for each treatment type respectively given historical expenditure data. For Major Rehabilitation and Major Preventative Maintenance, expenditure data came from the resurfacing database for the state whereas Minor Preventative Maintenance data came from a localized Work Order database with county work order information as described in Chapter 2. Minor Preventative Maintenance expenditure data was limited to cost data for crack sealing, crack filling, strip sealing, and chip sealing. Unit costs were calculated as the total expenditure for each treatment category divided by the total centerline mileage for each fiscal year. The use of centerline mileage for unit cost is a major limitation of the described procedure. Ideally, survey miles, which were used for the creation of existing condition information and TPMs, would have been used for the calculation of a more accurate unit cost. However, determining the number of survey miles a project would be considered as is an extremely arduous and infeasible task at a network level and therefore, was not used. Data for interstate MR&R treatments was limited to Major Rehabilitation.

Table 9-

Table 12 summarize the expenditure data and unit costs for FY 2008-2017.

Table 9. Historical expense on interstate Major Rehabilitation, FY 2008-FY 2017

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Funds (Millions of US $)	27.7	30.9	34.4	97.9	29.0	14.9	23.2	6.6	67.8	83.5
Centerline Mileage (Miles)	5	26	39	45	26	16	18	6	48	73
Unit Cost (Millions of US $)	5.6	1.2	0.9	2.2	1.1	0.9	1.3	1.1	1.4	1.1
Yearly Escalating Rate (%)		-79.14	-23.93	142.56	-48.99	-14.78	40.56	-18.87	31.72	-19.10

Table 10. Historical expense on non-interstate Major Rehabilitation, FY 2008-FY 2017

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Funds (Millions of US $)	149.7	103.1	55.4	130.4	72.7	100.6	80.9	75.9	296.0	274.5
Centerline Mileage (Miles)	553	478	204	476	251	389	326	233	864	974
Unit Cost (US $)	270,829	215,640	270,929	273,879	289,180	258,705	247,918	326,340	342,522	281,878
Yearly Escalating Rate (%)		-20.38	25.64	1.09	5.59	-10.54	-4.17	31.63	4.96	-17.71

Table 11. Historical expense on non-interstate Major Preventative, FY 2008-FY 2017

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Funds (US$ in Millions)	8.6	91.9	68.8	25.8	64.9	83.5	5.2	6.2	3.2	29.4
Centerline Mileage (Miles)	46	498	387	109	330	364	28	27	20	301
Unit Cost (US $)	187,336	184,719	177,745	237,163	196,637	229,582	184,930	226,097	155,612	97,779
Yearly Escalating Rate (%)		-1.40	-3.78	33.43	-17.09	16.75	-19.45	22.26	-31.17	-37.16

Table 12. Historical expense on non-interstate Minor Preventative, FY 2008- FY 2017

Year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Funds (Millions of US$)	2.8	2.5	1.3	1.7	2.2	2.9	3.2	4.1	3.7	2.7
Centerline Mileage (Miles)	1,214	1,023	548	648	860	1,176	1,188	1,498	1,416	1,217
Unit Cost (US $)	2,330	2,448	2,294	2,657	2,532	2,433	2,709	2,765	2,584	2,240
Yearly Escalating Rate		5.07	-6.29	15.80	-4.69	-3.94	11.37	2.07	-6.55	-13.30

For the purpose of the model, one unit cost for each treatment category was needed. To calculate the unit costs for Major Rehabilitation for interstates and non-interstates, Major Preventative Maintenance for non-interstates, and Minor Preventative Maintenance for non-interstates, the unit costs for each treatment category from FY 2008 to FY 2017 were plotted against time. The normality of data for each treatment category was then checked using a Q-Q plot of the information. The four Q-Q plots for the original treatment data appear in

Figure 8-

Figure 11. As depicted in the figures, normality can only be assumed for non-interstate Major Rehabilitation and Minor Preventative Maintenance. In order to assume normality of data for interstate Major Rehabilitation data and non-interstate Major Preventative Maintenance data, extreme values needed to be removed. For interstate unit costs, data points from FY 2008 and FY 2011 were removed. These values which correspond to the right-most data points in

Figure 8**,** are considered outliers as the data points are more than 1.5 times the interquartile range away from the third quartile of the unit costs. For the case of non-interstate Major Preventative Maintenance, normality was achieved by removing data points from FY 2015-2017. These three years' worth of unit costs correspond to the three data points with the greatest jump in cost between that data point and the next smallest unit cost per year.

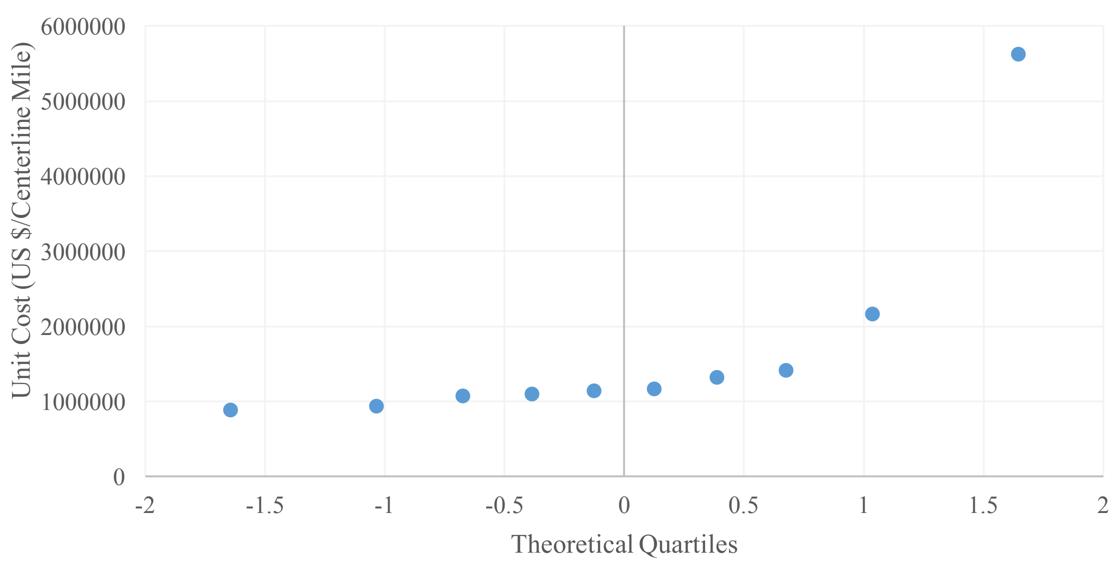

Figure 8. Q-Q Plot for interstate Major Rehabilitation unit costs from FY 2008-FY 2017

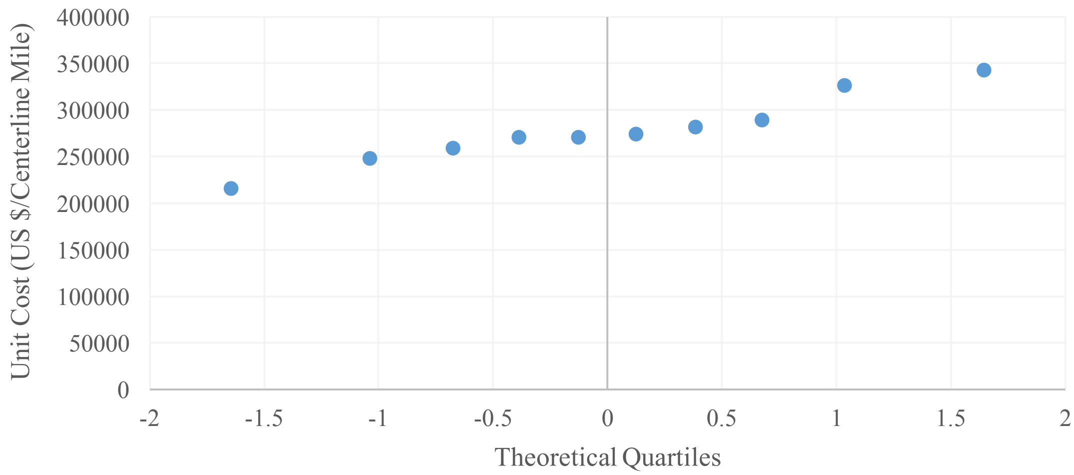

Figure 9. Q-Q Plot for non-interstate, Major Rehabilitation unit costs for FY 2008-2017

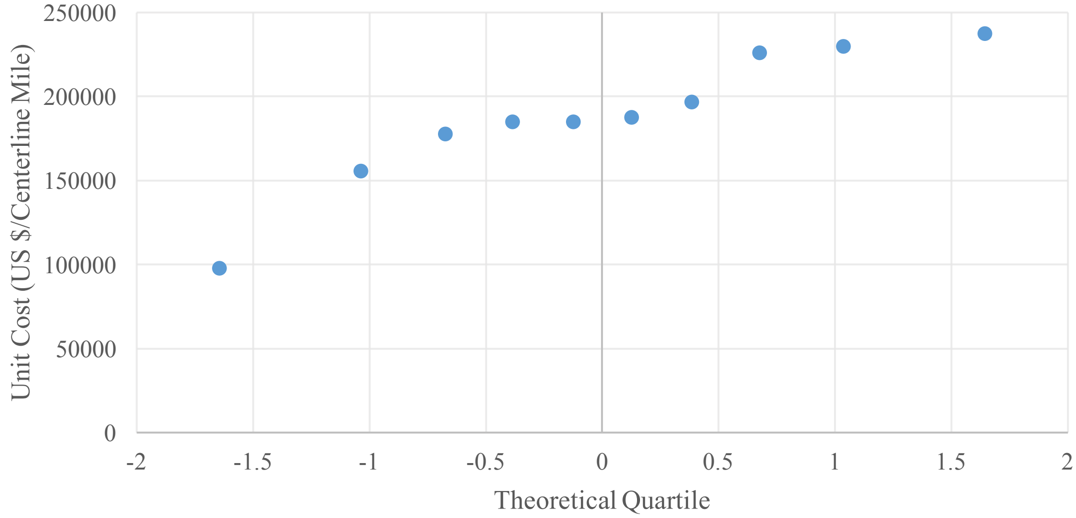

Figure 10. Q-Q Plot for non-interstate, Major Preventative Maintenance unit costs for FY 2008-2017

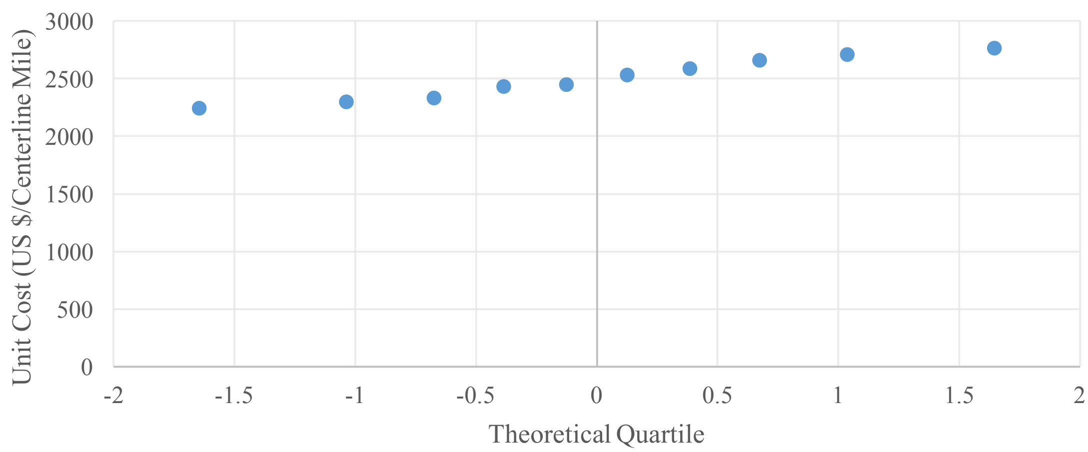

Figure 11. Q-Q Plot for non-interstate, Minor Preventative Maintenance unit costs for FY 2008-2017

Using a simple linear regression, the unit cost for each treatment type for non-interstates was forecasted to FY 2018, or Year 0 for the prediction model, using the resulting linear equation determined for each treatment after removing extreme values. In doing so, the aim was to normalize the fluctuation of unit costs over time.

Figure 12-

Figure 14 display the unit costs per treatment as a function of time for each treatment type for non-interstates. The resulting unit costs are summarized in **Table 13.**

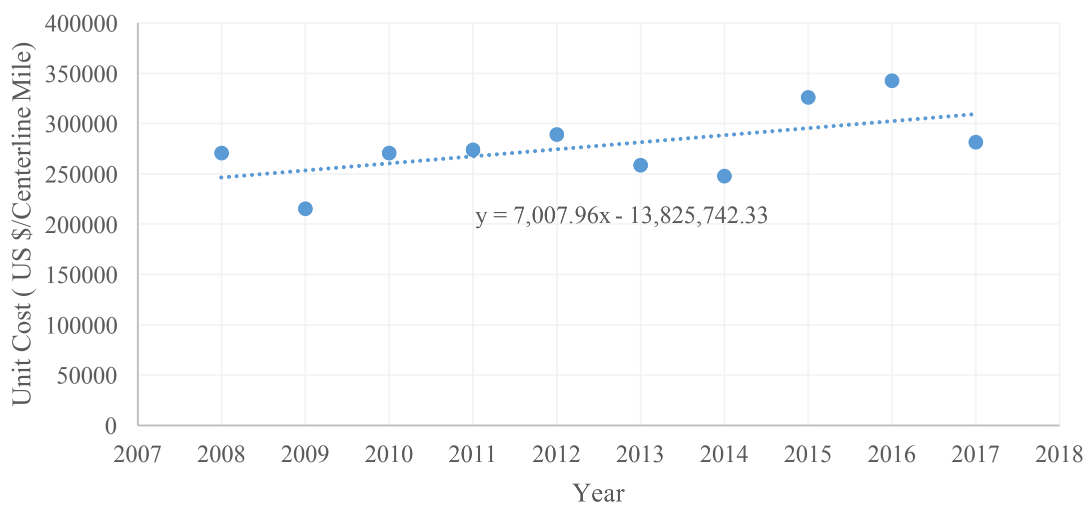

Figure 12. Unit cost over time for Major Rehabilitation for non-interstates

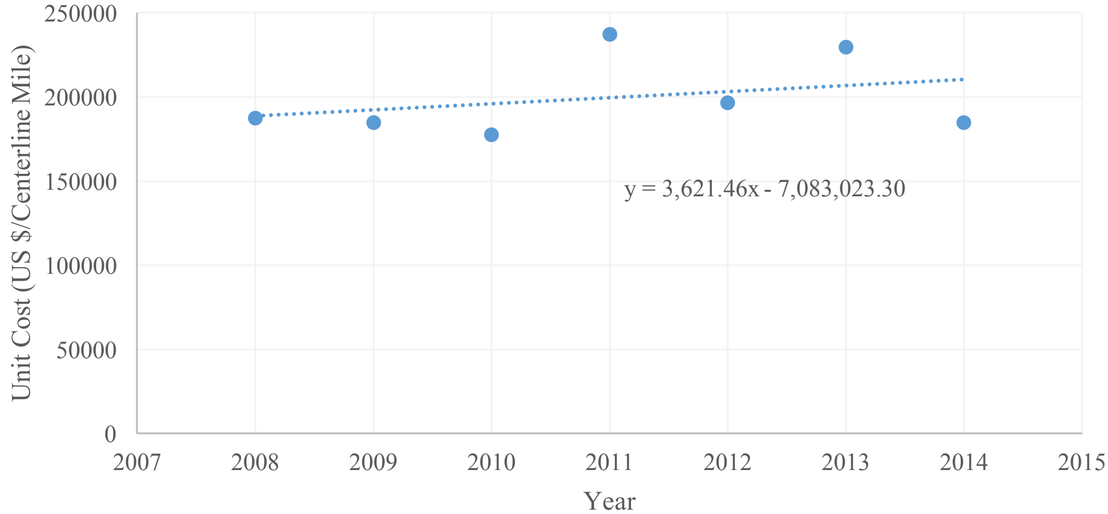

Figure 13. Unit cost over time for Major Preventative Maintenance for non-interstates

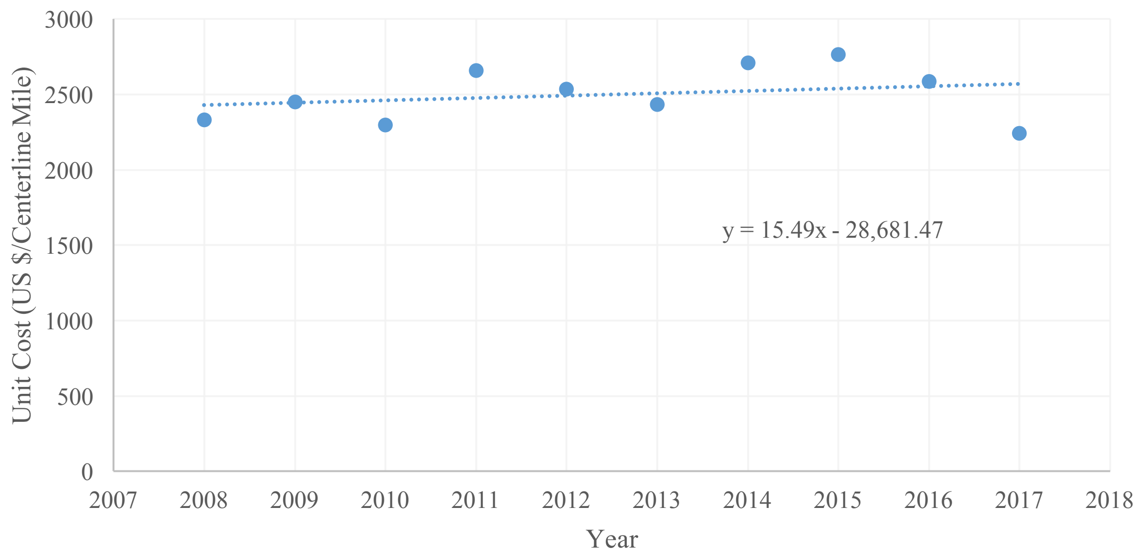

Figure 14. Unit cost over time for Minor Preventative Maintenance for non-interstates

Table 13. Unit costs for treatment types for non-interstates

Treatment Category	Unit Cost (US $/Centerline Mile)
Major Rehabilitation	316,321
Major Preventative Maintenance	225,083
Minor Preventative Maintenance	2,577

For interstate treatment costs, a similar procedure for calculating unit costs was conducted. However, because data was limited to Major Rehabilitation costs, Major and Minor Preventative unit costs were calculated as a percentage of the Major Rehabilitation unit cost. Based on the unit costs for non-interstates, Major Preventative unit costs were estimated to be 70% of the unit cost of Major Rehabilitation while Minor Preventative Maintenance was estimated to be 1% of the unit cost of Major Rehabilitation. It is recommended that more accurate estimates supported by data be used in the future. The unit cost of Major Rehabilitation was calculated using the linear regression equation of unit costs over time.

Figure 15 displays the unit costs for Major Rehabilitation as a function of time for interstates projects. The unit cost for FY 2018 was estimated to be $1,265,150/centerline mile for Major Rehabilitation. The rest of the treatment costs are summarized in

Table 14.

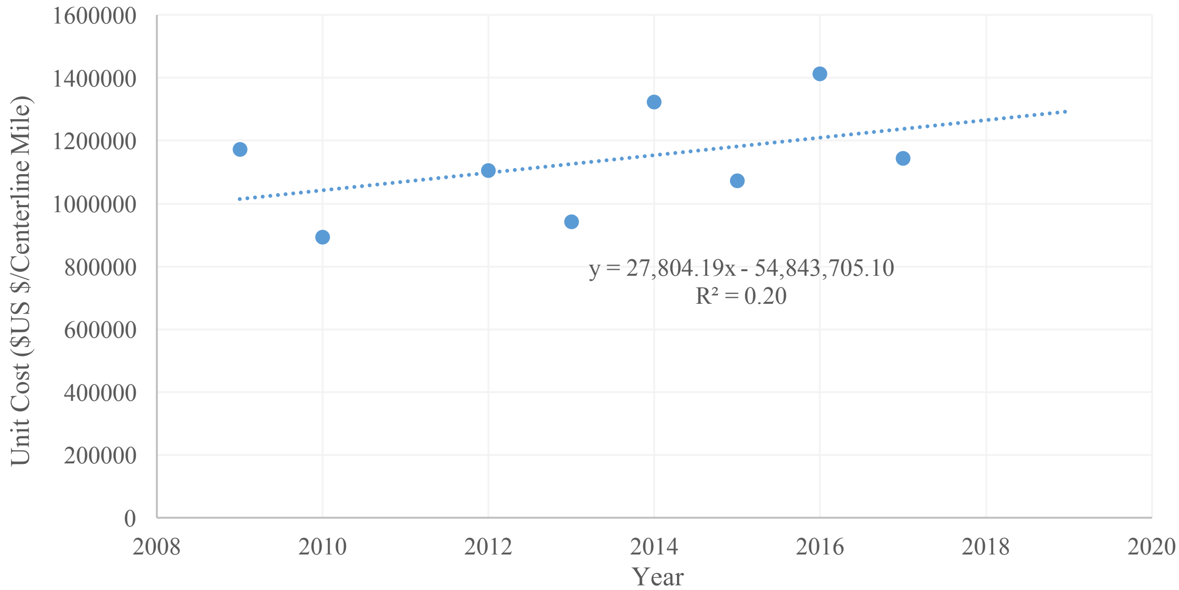

Figure 15. Unit cost over time for Major Rehabilitation for interstates

Table 14. Unit costs for treatment types for interstates

Treatment Category	**Unit Cost (US $/Centerline Mile)**
Major Rehabilitation	1,265,150
Major Preventative Maintenance	885,605
Minor Preventative Maintenance	12,652

Ideally, unit costs for each of the 35 pavement families would have been calculated and incorporated into the model. However, because the data provided could only truly be separated into non-interstate and interstate treatments due to the limited number of projects used to calculate unit costs, the unit costs calculated for interstate projects apply to all interstate projects regardless of working district and state route priority and the unit costs for non-interstates apply to all non-interstate projects regardless of working district or state route priority.

3.2.6.2 AAER Calculation

The Annual Average Escalating Rate (AAER) is the increase in the price of a service or good over a period of time. The escalation rate is important for prediction of MR&R costs in the future as it helps adjust for cost increases in the future. Escalation costs per year per treatment type were calculated as the difference between the unit cost of the current year and the previous year over the unit cost of the previous year for a particular treatment. Therefore, for a treatment type such as interstate Major Rehabilitation, nine annual escalation rates were calculated for the ten years of data. Subsequently, annual escalation rates for each treatment type were averaged by treatment. As with the unit costs, data removed to improve data normality were not included in the calculation of the AAER for that treatment. The AAERs for Major Rehabilitation for interstates and non-interstates, Major Preventative Maintenance for non-interstates, and Minor Preventative Maintenance for non-interstates were found to be -9.93%, 1.79 %, 1.41%, and -0.05% respectively. While these average escalation rates vary for each treatment type, an AAER of 1.79% was decided for use in the model as the number is most aligned with the average National Highway Construction Cost Index between FY 2008-2017 of 1.60% (FHWA, 2018). The calculated AAER and unit costs determined in the previous subsection can be used to predict future MR&R costs using the single-payment with discrete compounding equation:

$$C_t = C_0 \times (1 + AAER)^t \tag{1}$$

where C_t is the unit cost at t years and C_0 is the initial unit cost. For the purpose of the model, the initial cost used is the unit cost for each treatment category.

3.2.6.3 Integration of Cost into Model

Using the calculated unit costs and AAER, the cost of network maintenance can be predicted. For each year of prediction, the corresponding mileage that falls into the "Fair", "Poor", and "Bad" condition states can be calculated using the developed TPMs and subsequently, the model can choose to treat some or all of the projects in these categories as described by

Table 8. If a project is treated, the costs for that year are calculated using the single-payment compounding equation where Year 0 is FY 2018. Additionally, the performance of the pavement for subsequent years will follow the rules in

Table 15.

Table 15. Performance of pavements after treatment applied

Treatment	Performance
Major Rehabilitation	Pavement condition will increase to Excellent.
Major Preventative Maintenance	Pavement condition will increase to Excellent.
Minor Preventative Maintenance	Pavement condition will stay the same.

3.2.7 Summary of Existing Model and Modifications

Using the newly updated TPMs, unit costs, and AAER and introducing additional families which incorporate the state route priority, the Markovian model introduced in Research Project 05-19 was able to be updated and improved upon. The model is able to run a total of four strategies using the PMS model which include Optimization on Each Family, Optimization on All Families, Need Analysis, and Need Analysis on Each Priority Type which will be summarized in the subsequent subsections. Details about the notation, linear programming, and Markov Model verification, which are consistent with the original model are discussed in Sections 3.3.3.1 through Section 3.3.3.5 of Tsai, Wang, and Purcell (2010).

3.2.7.1 Optimization on Each Family

Optimization on Each Family is a simulation strategy used to identify the optimal or maximum composite rating for each family in the network given an annual budget each family will be given. Linear programming is used to optimize the condition rating of each of the 35 families created. Optimization for Each Family is an important simulation strategy as it allows each family to receive a specific amount of funding. Enabling funding to differ for families allows for optimal MR&R strategies to be created across different state route priority categories and for interstates vs. non-interstates.

3.2.7.2 Optimization on All Families

Optimization over All Families, similar to the first simulation strategy, utilizes a given annual total budget to maximize the composite rating of the entire network. Unlike the first strategy, linear programming is used to achieve optimization over the entire system rather than over 35 families. Optimization on All Families is useful for long-term pavement performance predictions.

3.2.7.3 Need Analysis

Need Analysis refers to a simulation strategy where a minimum performance standard can be set for the entire network of pavements. Using Need Analysis, the system can be restrained by a network composite rating and the percent of pavements in Poor or Bad condition. The default settings of this strategy are to constrain the network composite rating to 85 or greater and to restrict the percentage of pavements in Poor or Bad conditions to ten percent of the network. In using this strategy, linear programming outputs the minimum budgets needed to achieve these system or network requirements. The Need Analysis strategy is recommended for determining short-term budgets or supporting legislation to increase spending on MR&R activities.

3.2.7.4 Need Analysis on Each Priority Type

The Need Analysis on Each Priority Type simulation strategy is similar to the Need Analysis on the entire network. Using this approach, the user can determine the minimum composite rating required for each state route priority category for interstates and non-interstates. In total, five separate composite ratings are needed for the purpose of the simulation (Non-interstate Critical, High, Medium, and Low and Interstate Critical). Through the use of the Need Analysis on Each Type, the goal is to determine the minimum funding required to achieve these differing composite scores. The strategy enables more freedom in determining performance goals on pavements with differing priority levels.

3.2.8 Model Validation

The model described throughout this chapter was utilized to create a program that easily predicts budgets or performance based on the strategies previously described. The program which was modified from the existing GDOT LP&S program from Project 05-19 was utilized to assess the validity of the Markovian strategies implemented throughout the chapter. Model validation was based on the comparison of historical pavement condition data in **Table 4** and **Table 5** to that output by the model. While data for both non-interstates and interstates exists, only non-interstate data was used for the validation of the model as interstate data is both too small in mileage therefore limiting accuracy and too variable in terms of expenditure.

To properly compare the historical data to the outputs of the developed model, the model was ran to predict pavement condition from FY 2010- FY 2015. In terms of the scenario ran to achieve a prediction similar to the historical performance, Optimization on All Families using an annual budget of $190 million dollars and unit costs from FY 2010 were used. These inputs were based on historical expenditure data and engineering judgment. The scenario was ran for multiple TPMs in order to find the best transition probabilities for the Fair and Poor pavement conditions as alluded to in Section 3.2.5.

As depicted in **Table 16** and **Figure 16-Figure 21,** the developed model is consistent with the historical pavement performance based on both condition states and composite rating. The mean difference between the simulated results and historical data ranged from 1.1 to 8.2 with the greatest difference between the model and historical data corresponding to the percent of the network in the Poor category. The variance in the average difference for the six years of data was minute with all variances being less than 1. When comparing the average composite rating, the mean difference between the model and the historical data was 0.96, and the variance was 0.31. The results of the comparison validate the use of the model within a certain level of error.

Table 16. Difference between Markov model results and historical data

	Mean	Variance	Maximum
Excellent (%)	1.1	5.5 E-5	2.1
Good (%)	3.7	4.5 E-4	5.7
Fair (%)	2.4	2.7 E-4	5.1
Poor (%)	8.2	6.0 E-4	11.6
Bad (%)	1.5	9.9 E-5	3.5
Composite Rating	0.96	0.31	1.81

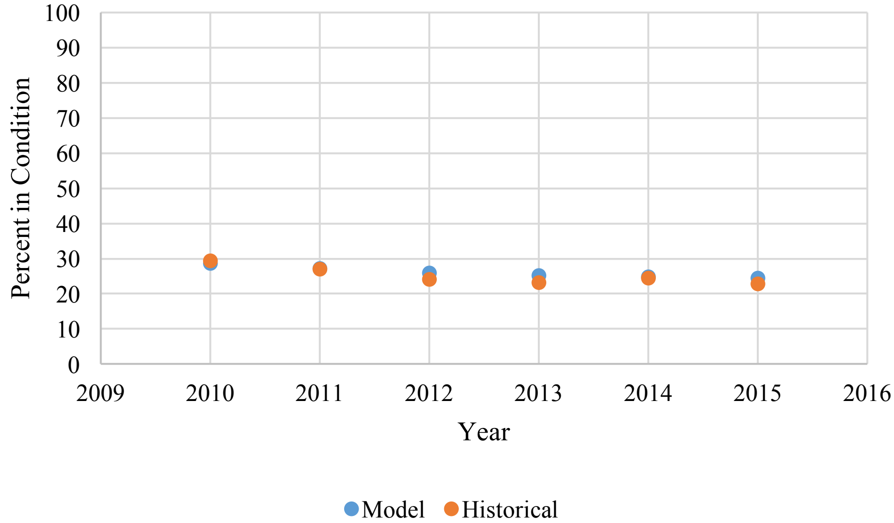

Figure 16. Comparison of model and historical percent of pavements in Excellent condition

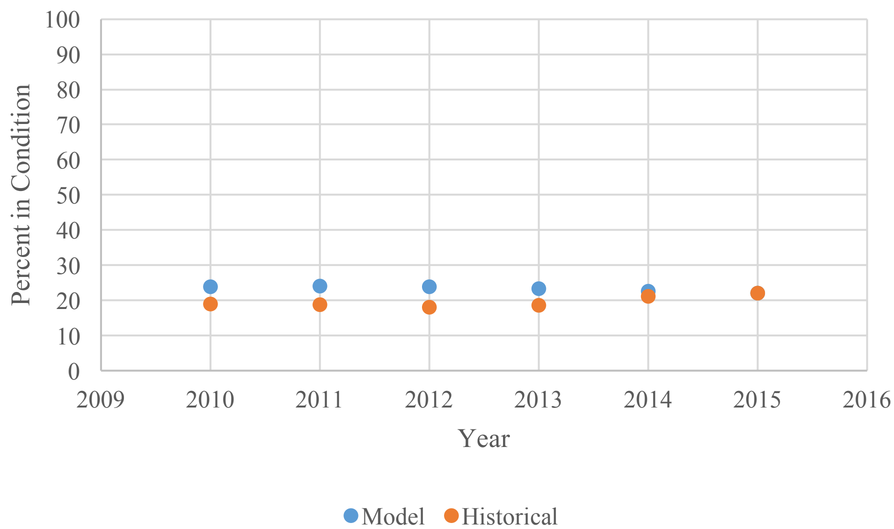

Figure 17. Comparison of model and historical percent of pavements in Good condition

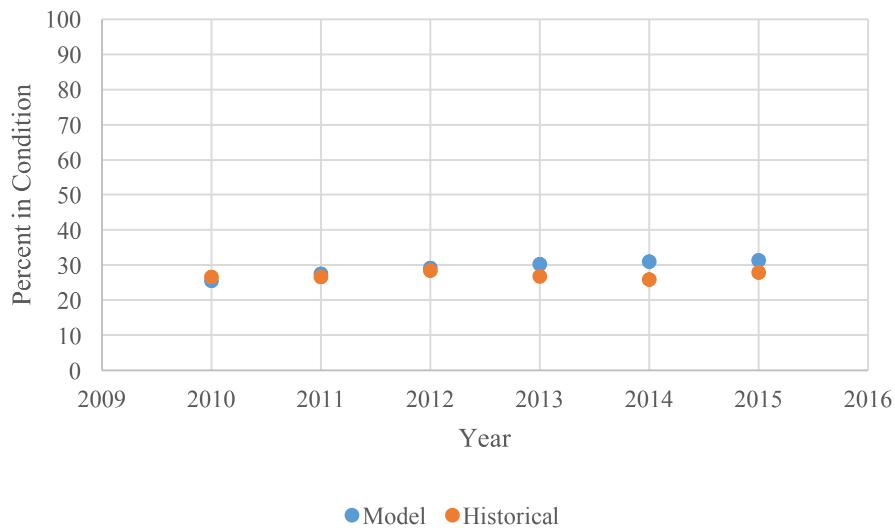

Figure 18. Comparison of model and historical percent of pavements in Fair condition

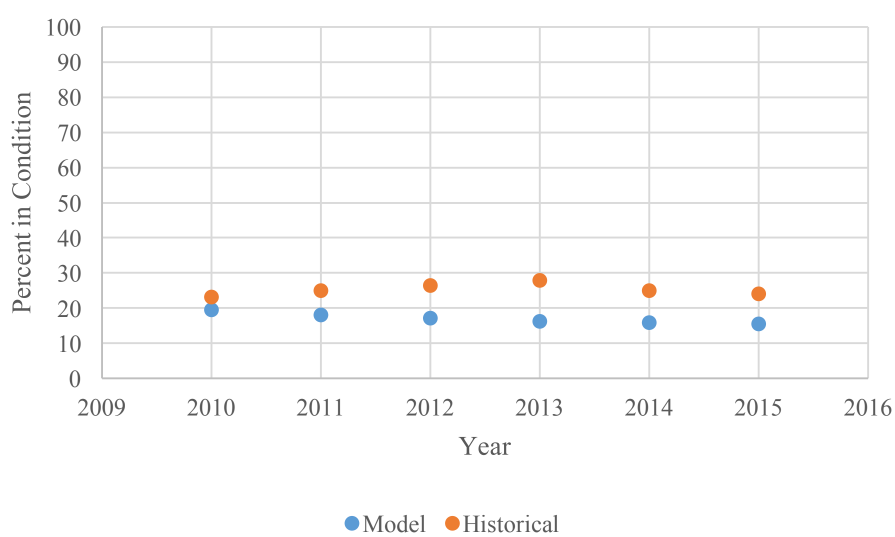

Figure 19. Comparison of model and historical percent of pavements in Poor condition

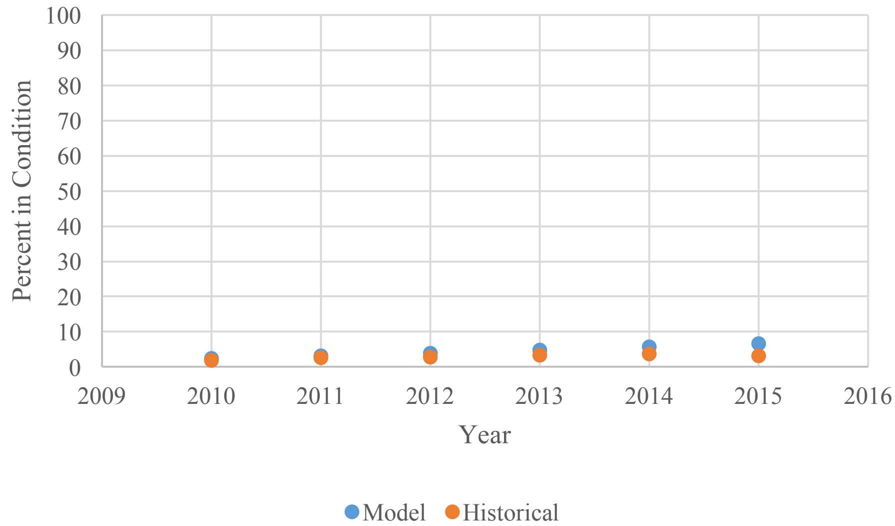

Figure 20. Comparison of model and historical percent of pavements in Bad condition

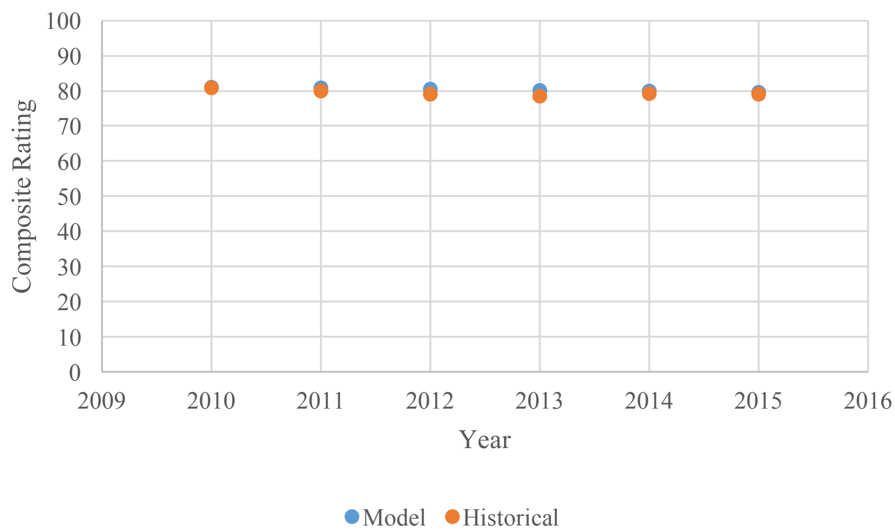

Figure 21. Comparison of model and historical composite rating

CHAPTER 4. TRIGGER CRITERIA FOR MAINTENANCE AND REHABILITATION TREATMENTS

Within the state of Georgia, the use of preventative maintenance to enhance pavement life began in the 1970s, making the state a leader in the application of these treatments. Preventative maintenance treatments within the state of Georgia includes strip seal, mill and overlay, chip seal, and crack sealing amongst others. While many of these preventative treatments have been used for over four decades in the field, a comprehensive understanding of each's effectiveness in enhancing the pavement performance of a segment or project has not been thoroughly studied. While some research has been conducted by Tsai et al. (2010) on trigger criteria under which treatments, particularly crack sealing, are most effective, lack of data prevented a comprehensive study on the role crack sealing plays on pavement life. Georgia's record of treatment history began more recently with some of the first records of treatment application within the COPACES beginning in 1999. As the segments or projects on which these treatments were applied begin to age and therefore, as a history of performance for treated segments and projects becomes available, the data becomes more useful in determining best practices.

In this chapter, the objective is to use crack seal as a case to illustrate how to use trigger criteria for a treatment. The goal is to optimize the life of the pavement and therefore reduce spending for the GDOT in the long-term. Specifically, the chapter will analyze the best practices for crack sealing by presenting the current practices in crack seal application throughout the United States and by conducting a segment-level analysis of the effects of crack sealing on pavement performance. As more data is collected on other treatments conducted by the Georgia Department of Transportation, it is recommended that an analysis of the best practices for each new treatment be conducted and implemented into the PMS.

4.1 Crack Sealing Literature Review

According to a survey conducted by Ragab et al. (2013) approximately 76 percent of transportation entities surveyed considered crack sealing or crack filling as their primary treatment for crack maintenance. As pavements deteriorate and cracks develop in pavements over time, crack filling/sealing is often used and considered a cost-effective means of pavement preservation. Crack sealing, refers to a treatment that is typically used on working cracks, or cracks with greater than 3 mm of movement throughout the year (Caltrans, 2003). Crack filling, contrarily, is commonly used on “nonworking” cracks which do not expand or shrink more than 3 mm throughout the year. Typically, crack sealing is used on transverse cracks, and crack filling is more prevalent on longitudinal cracks. Both treatments are focused on preventing the intrusion of water and material into existing pavement cracks (Caltrans, 2003; Decker, 2014; Ragab, Waldenmaier, & Abdelrahman, 2013). While crack sealing and crack filling are distinct treatments, the National Cooperative Highway Research Report Program Report 784 found that these two terms are used interchangeably by 62 percent of agencies surveyed (Decker, 2014). Therefore, for the purposes of this report, crack sealing will be used to refer to any form of crack sealing or crack filling as is common within the state of Georgia. The next sections explore research that has been conducted on crack sealing.

The research helps answers the questions of 1) which pavements should receive crack sealing/filling as a treatment, 2) what are the best practices for the application of crack sealing/filling, and 3) what is the effect of these treatments on pavement performance. In doing so, the aim is to understand the needs for further crack sealing research.

4.1.1 Site Selection

Both federal and state research have shown that crack sealing or filling is not appropriate for all pavements with cracking present. Instead, most studies have recommended crack sealing be applied to sites with longitudinal, transverse, reflective, or block cracking and a sound base or subbase (Decker, 2014). Wood et al. (2009) further emphasizes the importance of the pavement base and condition when considering crack sealing for a site. The author explains that sites with reduced levels of load-related distresses, rutting, and maintenance activities are suitable for crack sealing (Wood, Olson, Lukanen, Wendel, & Watson, 2009). In terms of the characteristics of the cracks, standard practice suggests that crack width should be between 3 mm and 25 mm in order for the treatment to extend pavement life (Caltrans, 2003). Additional considerations for site selection may include climate, highway classification, traffic level, truck percent, crack characteristics and density, and material and material placement (Ragab et al., 2013).

4.1.2 Best Practices

Current best practice manuals on crack maintenance and crack sealing are focused on the best construction mechanisms, materials, and timing. In terms of construction practices utilized for crack sealing, sealing most commonly takes on the form of flush fills, simple band aid, capped, reservoir fill, combination fill, and sand-filled with recessed finish (Caltrans, 2003). These six distinct methods are seen throughout the literature with the band aid and reservoir fills used frequently in studies on crack sealing effectiveness especially with regards to transverse or working cracks (Fang, Haddock, Galal, & Ward, 2003; Johnson, Freeman, & Stevenson, 2000).

The fill method's usefulness is also complemented by whether the material is applied using a hot or cold pour application. Research has underscored the benefit of using hot pour applied rubber compared to cold pour asphalt as hot pour asphalt has been proven to perform better in most environments (Caltrans, 2003; Yildirim, Korkmaz, & Prozzi, 2006a). In most cases, the material used for crack sealing or filling is a variation of a rubber asphalt sealant. In the state of Georgia, sealing where no overlay is conducted utilizes Type S polymer-based asphalt rubber with a minimum of 15 percent rubber content (GDOT, 2013).

A final consideration often considered as a best practice is the time of year that crack sealing is applied. According to a survey conducted on best practices of crack sealing, a majority of state and local agencies stated they conduct construction processes related to crack sealing in the spring and fall months (Caltrans, 2003; Ragab et al., 2013). Yildirim, Qatan, and Prozzi (2006b) supports that practice, concluding that the best time to seal cracks is during a period where crack width is at its midpoint, around 45- 60 degrees Fahrenheit. Applying crack sealant under a moderate temperature ensures the crack is neither overfilled nor under filled due to the contraction and expansion that occurs with seasonal temperature changes.

4.1.3 Effect on Performance

A final characteristic of crack sealing that research has aimed to address is how crack sealing affects the overall performance of a pavement. In understanding the answer to this question, the definition of failure or performance has to be defined. In the literature, material failure and physical failures are some of the more commonly defined failure types for crack sealing. Material failure typically refers to the crack sealing material used failing. This can occur through adhesion or the rubber's inability to adhere to the sides of crack or through cohesion where a sealant fails in tension (Caltrans, 2003). Materials can also fail through pullouts where entire sealant materials are pulled from the crack by tire action (Caltrans, 2003; Yildirim, Yurttas, & Boz, 2010). Physical failures refer to crack sealing failing to divert water and debris that harm pavement and can be measured as combination of increased potholes, spalling, settlement, bleeding, and general loss of performance as calculated by a roughness, rutting, faulting, friction, or serviceability index (Caltrans, 2003; J. Li, Luhr, Russell, Rydholm, & Uhlmeyer, 2017; Yildirim et al., 2006a).

Crack sealing performance or the effect of crack sealing on the performance of pavement is also closely studied in previous literature. Most studies measure the effect of crack sealing in terms of extension of pavement life or through condition metrics. **Table 17** provides a summary of some of the key studies that focused on answering how long crack sealing was able to extend pavement life. While the differences in the variables considered and the methods used to calculate pavement life vary, the general extension of service life when crack sealing is applied is approximately 2 years. A gain in service life can also be equated to cost savings. Ponniah and Kennepohl (1996) aimed to study the pavement life benefits of crack sealing through an analysis of costs incurred for a pavement segment when crack sealing was applied both 4 and 8 years following a reconstruction and when no crack sealing was applied leading to a major reconstruction. Based on the analysis, a 13 percent savings over a 30 year life was predicted by applying crack sealing.

Table 17. Summary of previous studies on pavement life extension from crack sealing

Study Citation	Extension in Pavement Service Life	Variables Considered
(Rajagopal, 2011)	1.85 years (3.9 PCI condition gain)	-Pavement type (flexible or composite) -Aggregate on Surface (limestone or gravel) -Pavement Condition Rating (<75, 75-85, or >85)
(Fang et al., 2003)	0 years	-Pavement type -Drainage condition -Road classification
(Ponniah & Kennepohl, 1996)	2 years	-Rout size
(Yildirim et al., 2010)	6 months to 2 years	-Sealant type (Hot or cold pour)
(J. Li et al., 2017)	3 years	-N/A

While most studies are able to answer the question of how long crack sealing can last or what are the benefits of crack sealing, few have successfully answered the question of when the best time to treat a road with visible cracking is. Rajagopal (2011) aimed to answer this question by studying the effect of the Pavement Condition Rating of a pavement before crack sealing is applied on the pavement service life extension due to crack sealing. The study found a Pavement Condition Rating between 66-70 points had the highest computed service life extension when crack sealing was applied. The study also considered the effects of pavement type and aggregate at the surface on the overall performance of cracking sealing. Studying factors that affect how crack sealing performs is key to understanding when crack sealing will be most effective. However, the findings of studies that look at these factors such as Rajagopal (2011) are limited by their lack of generalizability to other states within the country as conditions affecting pavements from state to state vary. Therefore, the need to create a framework for state or local entities to perform their own analyses that helps determine best practices for the application of crack sealing exists. While previous literature provides good examples of experimental studies that help determine crack sealing trigger criteria, the development of an easily implemented and cost-effective framework for studying crack sealing would provide significant value.

4.2 Segment-Level Study on Crack Sealing within the State of Georgia

From the literature review, it is evident that understanding when and where is best to implement crack sealing is important. While other studies have attempted to answer these questions, the generalizability of their results to the conditions within the state of Georgia is unknown. Therefore, the aim of this section is to conduct an analysis to determine when and where is best for crack sealing within the state. The analysis conducted is focused on using data already collected by the state and therefore, will provide a helpful framework for similar analyses to be conducted by other states throughout the country.

4.2.1 Data Description

The data used for the purpose of this analysis was pulled from the Georgia Pavement Management System and includes historical COPACES segment-level survey data from FY 1986 to FY 2015. Each entry in the system includes two types of information about the segment—segment location information and segment survey information. The segment location information has 14 fields including the mile post start and end for each segment (SEGMENTFROM and SEGMENTTO), county number, route number, whether crack sealing was observed on the segment, and the Segment Rating as summarized in the Appendix E. The segment distress information includes 29 fields with information related to the rutting, block cracking, loading, raveling, and reflective cracking in addition to other distress information summarized in the Appendix E. In addition to segment-level data provided in COPACES, the project-level data from GPAM was drawn upon to get additional information about the road characteristics that a segment is a part of. Despite the volume of data provided by the GPAM system, there was still a need to assess the quality of the data provided. Section 4.3 details the data processing procedure used to assess and improve the quality and validity of the raw data.

4.2.2 Data Assumptions

Data assumptions required in the analysis of the segment-level data are numerous. However, the major assumptions can be summarized into two major categories: 1) assumptions about when crack sealing is truly observed and 2) assumptions about the Segment Rating when crack sealing is observed.

The key field necessary in the analysis of the crack sealing performance is the "CRACK SEALED" category referred to in the Appendix E. The field, which can be marked "YES," "NO," or left blank, determines whether crack sealing was observed during the segment-level survey that year. Accordingly, when a segment transitions from a "NO" to "YES" initially, it is assumed that crack sealing was applied somewhere in between the two sequential FYs whereas when a segment transitions from "YES" to "NO" in consecutive years, it is assumed that the crack seal broke, treatment was applied (other than crack sealing), or reconstruction of the roadway occurred. Finally, if a "YES" is not observed and the "CRACK SEALED" field is empty within the GPAM system, there is an assumption that no crack sealing is observed during that period of time.

In addition to the assumptions made about when crack sealing was applied, an additional assumption was made about the Segment Rating at the start of the crack seal application. While ideally, the pavement performance of a segment would be measured from the year before crack sealing was applied, because the GPAM data had a lot of missing information at a segment level, the pavement performance under crack sealing was determined using the first year crack sealing was seen in the survey of the segment or the first year the "CRACK SEALED" category returned a "YES" for that segment.

4.2.3 Data Processing

As discussed in Section 3.2.2, the methods used to process data are key for valid analysis and results. In the two sections that follow, the procedure for data processing that occurred at a segment level and was used to determine the performance of crack sealing as a treatment is described. The data processing procedure at a segment level can be divided into two phases 1) initial data processing which removes data with missing fields and 2) duplication removal.

Figure 22 provides a schematic of the overall data processing procedure below.

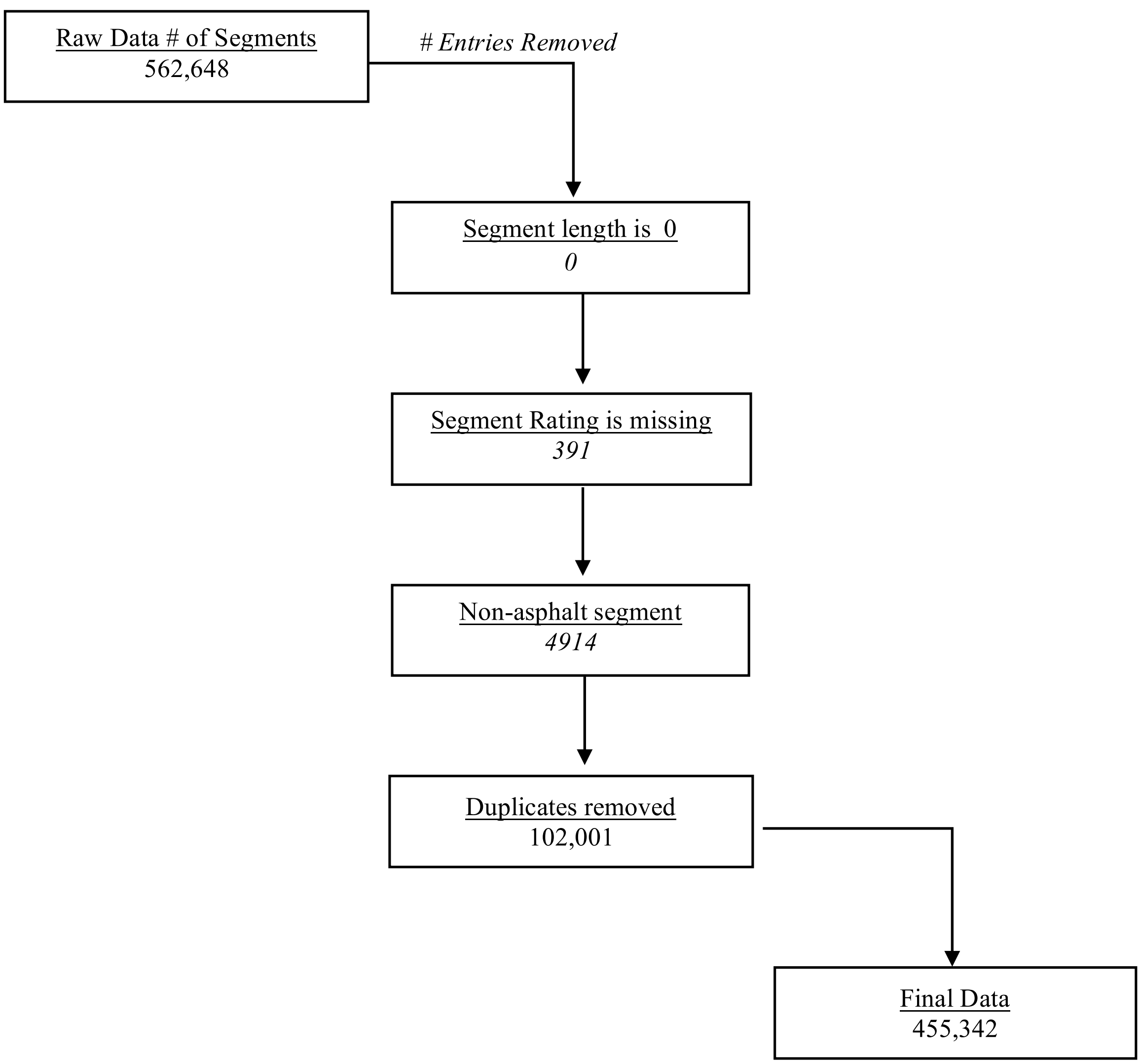

Figure 22. Data processing procedure at a segment level

4.2.3.1 Initial Data Processing Procedure

In order to properly utilize segment-level COPACES data, the total dataset of 562,648 entries had to be processed before analysis on crack sealing performance began. As discussed in Section 4.2, raw data included three forms: segment-level location information, segment-level distress information, and project-level location information. These three data sets were linked by their trip dates, route numbers, and additional fields provided and given a unique ID so that each entry's segment and project information could be easily accessed.

The initial data processing procedure involved taking the linked raw data and checking to make sure each entry provided was useable. In particular, because the analysis of pavement performance for crack sealing relies upon multiple characteristics about the segment studied, entries in the GPAM system with missing critical field information were not used in the analysis performed. The main steps taken at this initial stage of the processing procedure can be summarized as the following:

1. Removal of entries where MilePostFrom or MilePostTo were both 0s, indicating a segment length of 0
2. Removal of entries with missing Segment Ratings
3. Removal of projects that were not asphalt

The number of segment entries removed at each phase of this initial process—0, 391, and 4,914 subsequently—is summarized in

Figure **22.**

Once these initial procedures have been carried out, the RCLINK was created for each segment using the process described in Section 3.2.2. A unique Segment ID was created to identify entries that analyzed the same areas of roadway by concatenating the RCLINK, SEGMENTFROM, SEGMENTTO, and lane direction fields of each entry. Once Segment IDs were created, Segment Rating trends over time could be analyzed and the second phase of data processing—duplication removal—began.

4.2.3.2 Duplication Removal

Duplication within COPACES data occurs at a segment level in addition to at a project level. In the case of segment-level information, duplication occurs when there are multiple entries for a unique Segment ID within the same year. Of the filtered 562,648 observations at a segment level, 102,001 of the entries were duplicates to be deleted. The number of duplicates number of entries is nearly one fifth of the total entries within the COPACES segment-level database signifying issues of data quality control at the segment-level. For each Segment ID in a particular year, there existed as many as five duplicate entries.

As at a project level, duplicates obfuscate trends within the data, making it difficult to understand the performance of a project or segment as well as the performance of treatments applied. In order to eliminate the lack clarity caused by duplication, data recorded the year before (denoted as Year 1) and the year after (denoted as Year 3) the year a segment had duplication were used to determine which entries to remove. Nine scenarios were used to decide which entry to choose in the case of the duplicates. The Segment Ratings before and after the year with the duplicate were classified into one of three categories: under construction or newly constructed (Segment Rating of 105 or 100), a non-newly constructed segment (Segment Rating from 1-99), or missing or an also duplicated entry. Below the nine scenarios using different combinations of these categories are defined and a procedure for choosing which entry to keep is described.

Scenario 1: *A missing/duplicated entry Year 1, a non-newly constructed segment Year 3*

If Year 3 has a Segment Rating greater than or equal to 75, the entry selected for Year 2 will have a Segment Rating approximately 5 points more than Year 3. Therefore, the entry where the difference between that entry's Segment Rating and Year 3's Segment Rating is closest to 5 will be selected.

If Year 3 has a Segment Rating less than 75, the entry selected for Year 2 will have a Segment Rating approximately five points more or less than Year 3. This assumes that when the Segment Rating is less than 80, preventative maintenance (which would increase the Segment Rating by approximately 5 points) could be applied. However, above a segment score of 80, it is unlikely for any maintenance to be suggested. Therefore, under these conditions, the entry where the absolute difference between the entry's Segment Rating and Year 3's Segment Rating is closest to 5 will be selected.

Scenario 2: *A missing/duplicated entry Year 1, an under construction segment Year 3*

If Year 3 is newly constructed or under construction with a Segment Rating of 105 or 100, the Year 2 duplicate selected would be an entry with a Segment Rating of 100 or 105 for that year or the lowest Segment Rating of all the duplicates if the previous conditions are not met.

Scenario 3: *A non-newly constructed segment Year 1, a missing/duplicated entry Year 3*

If the Year 1 Segment Rating is greater or equal to a Segment Rating of 80, the entry selected Year 2 will have a Segment Rating approximately 5 points less than Year 1. Therefore, the entry where the difference between Year 1's Segment Rating and the entry's Segment Rating is closest to 5 will be selected.

If the Year 1 Segment Rating is less than 80, the entry selected for Year 2 would be the entry where the absolute difference between the Year 1 Segment Rating and the entry's Segment Rating is closest to 5.

Scenario 4: *An under construction segment Year 1, a missing/duplicated entry Year 3*

If Year 1 is newly constructed or under construction with a Segment Rating of 105 or 100, the Year 2 duplicate selected would be an entry with a Segment Rating of 100 or 105 for that year or the highest Segment Rating of all the duplicates if the previous conditions are not met.

Scenario 5: *A non-newly constructed Year 1, an under construction segment Year 3*

If Year 1 is non-newly constructed or under construction segment but Year 3 is, the Year 2 duplicate selected would be an entry with a Segment Rating of 100 or 105 for that year. If none of the duplicates have a Segment Rating of 100 or 105, then the Year 2 selection will follow rules established in Scenario 3.

Scenario 6: *An under construction segment Year 1, a non-newly constructed segment Year 3*

If Year 1 is newly constructed or under construction segment but Year 3 is not, the Year 2 duplicate selected would be an entry with a Segment Rating of 100 or 105 for that year. If none of the duplicates have a Segment Rating of 100 or 105, then Year 2 selection will follows rules established in Scenario 1.

Scenario 7: *A non-newly constructed segment Year 1, a non-newly constructed segment Year 3*

If both Years 1 and 3 are non-newly constructed segments with Segment Ratings less than 100, then the segment entry chosen for Year 2 should be a reflection of the trend between these two year's Segment Ratings. In particular, the segment entry with a Segment Rating closest to the mean Segment Rating of Year 1 and Year 3 should be selected if the Segment Rating of Year 3 is less than the Segment Rating of Year 1. If the opposite is true, then Year 2 selection follows Scenario 5.

Scenario 8: *An under construction segment Year1, an under construction segment Year 3*

If Year 1 and Year 3 are newly constructed or under construction with a Segment Rating of 105 or 100, the Year 2 duplicate selected would be an entry with a Segment Rating of 100 or 105 for that year. If none of the duplicates have a Segment Rating of 100 or 105, then due to lack of decision-making information, all duplicates for Year 2 are advised to be deleted.

Scenario 9: *A missing/duplicated segment Year 1, a missing/duplicated segment Year 3*

If both the data for Year 1 and Year 3 are missing/duplicated, then due to lack of decision-making information, all duplicates for Year 2 are advised to be deleted.

Other Scenarios

For scenarios that fall outside of these nine prescriptive scenarios, duplicate removal was done manually using the data analyst's best judgement.

Example Scenario

For the purpose of illustrating the procedure taken for duplicate removal, suppose a segment which is identified by the SegmentID 86103760077.2POS has duplicate entries in FY 2010. One of the duplicate entries for that year has a Segment Rating of 88, and the other has a Segment Rating of 55. In order to determine which entry must be deleted, information about the segment before and after FY 2010 will be used. In this case, suppose Year 1 for SegmentID 86103760077.2POS, FY 2009, has a Segment Rating of 90 and Year 3, FY 2011, for that ID has a Segment Rating of 85. Under these conditions, Scenario 7 would apply. In Scenario 7, the entry with the Segment Rating closest to the mean of Year 1 and Year 3 is kept. In this example, the average of Year 1 and Year 3 is a Segment Rating of 87.5. Therefore, the entry with a Segment Rating of 88 would be kept, and the entry with a Segment Rating of 55 would be deleted.

4.2.4 Results on Crack Sealing Performance

In this section, an analysis of the performance of crack sealing at a segment level will be conducted. The data used in the analysis is the data described in the previous section as 455,342 entries of segment-level data or 116,494 groups of segment information from FY 1986 to 2015. The analysis is organized as follows: data definitions, data aggregation, performance analysis, and finally, data limitations. The details of each of these procedures are described in the subsections to follow.

4.2.4.1 Data Definitions

In order to properly analyze the segment-level data, established terminology must be defined. The table below summarizes commonly used terms throughout this section as well as their respective definitions.

Table 18. Segment-level data definitions

Term	Definition
Start Year	First year crack sealing was observed on a segment (first year “CRACKSEALED” category was equal to “YES”)
Consecutive Count	Total number of years in a row that crack sealing was observed on a segment
End Year	Last year crack sealing was observed on a segment (last year “CRACKSEALED” category was equal to “YES”)
Life 70 of Crack Seal	The number of years until a pavement reaches a COPACES Segment Rating of 70 calculated from the Start Year of crack seal application

4.2.4.2 Data Aggregation Results

The aim of this subsection is to describe the general characteristics of the aggregated segment-level data in terms the Segment Rating the first year crack sealing is applied and the typical number of years that crack sealing is observed. The results are explained below.

Start Year of Crack Seal Application

The question of when crack sealing is currently being applied in the state of Georgia was addressed by plotting the distributions of two important features: the Segment Rating of segments the year before segments received crack sealing and the Segment Rating of segments the first year crack sealing was observed. By plotting this information, it was found that the Segment Rating the year before crack sealing was applied had a mean Segment Rating of 69.75 whereas the mean Segment Rating the first year crack sealing was observed was slightly higher at 73.23. It is likely the difference in means between the two years can be attributed to the number of missing observations for the Segment Rating the year before crack sealing was applied or the additional gain in performance assumed by applying crack seal. The distribution of when crack sealing was first observed is summarized in the figures below.

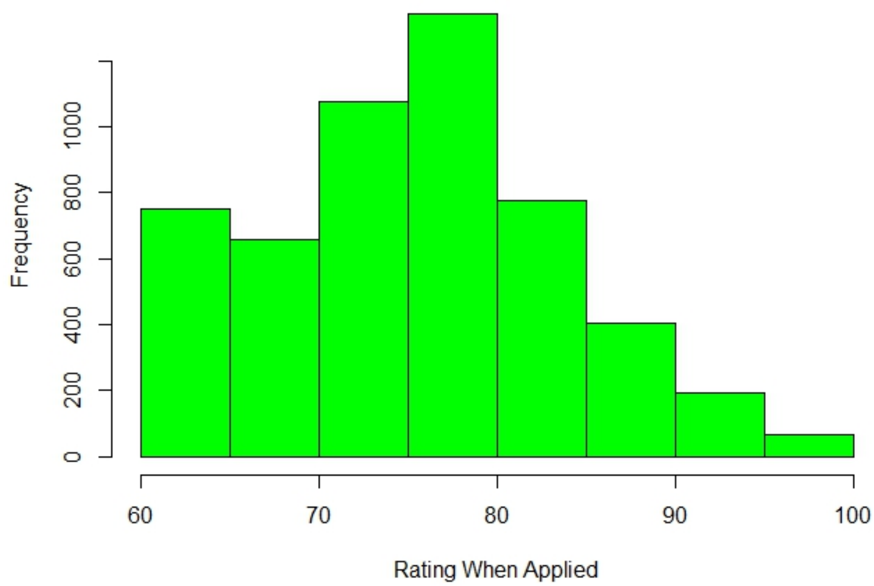

Figure 23. Distribution of Segment Ratings the first year crack sealing was observed

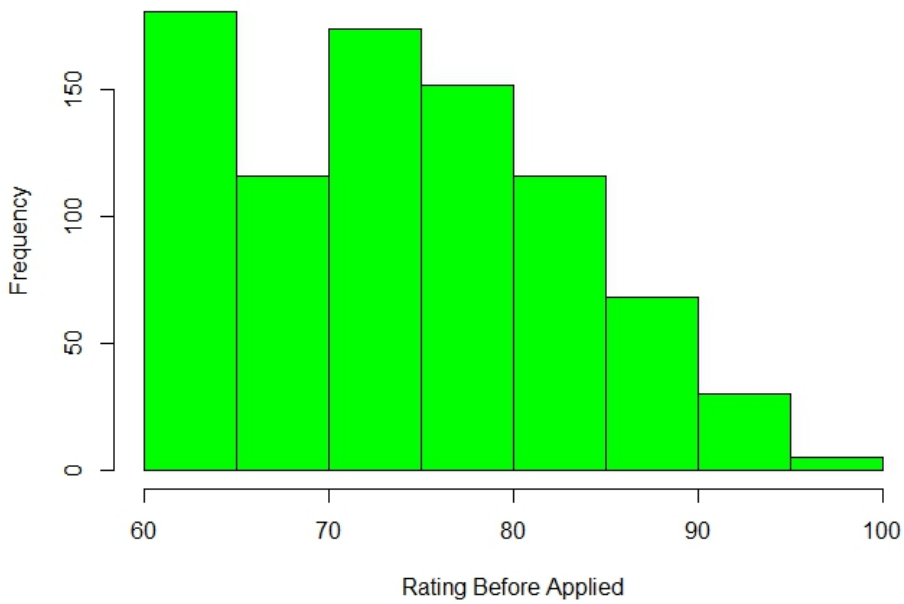

Figure 24. Distribution of Segment Ratings the year before crack sealing was observed

Consecutive Count of Crack Seal Application

A second question addressed about the segment-level information provided by GPAM was how many consecutive years of crack sealing is typically observed. While data quality played a large role in shaping the distribution of number of consecutive years of data where crack sealing was observed, the mean number of years was 2.087. The figure below shows the distribution of the data set.

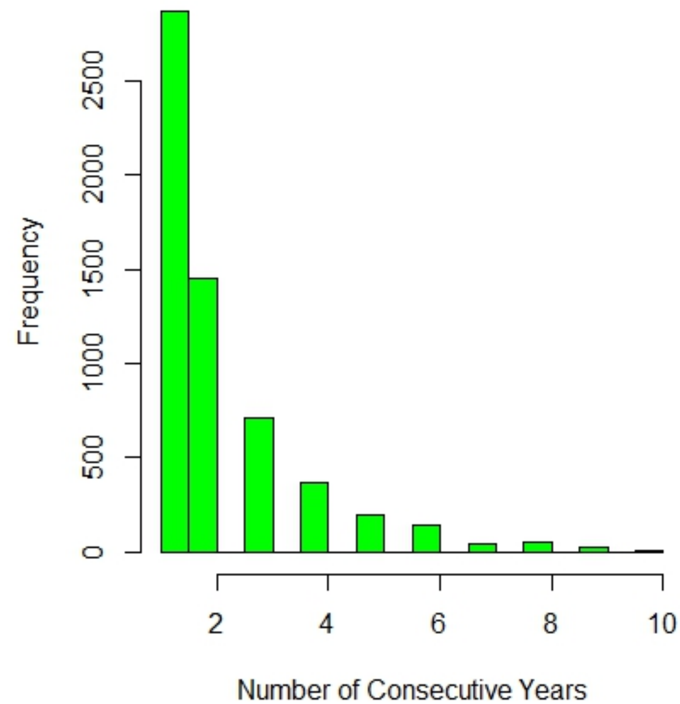

Figure 25. Distribution of number of consecutive years crack sealing is observed

4.2.4.3 Network-level Performance Analysis using Condition Rating

In order to analyze performance of the crack sealing as a treatment, a comparative study was conducted. In this study, the Life 70 of all segments with crack sealing applied and segments with no treatment applied were determined and compared. Because crack sealing is not typically applied when the pavement is in good condition, the Life 70 of segments were determined using differing Segment Ratings at the crack sealing project's Start Year. Similarly, the Life 70 for segments where no treatment was applied was calculated at differing Segment Ratings for the Start Year. The justification for use of

Life 70 for comparison is that it is a comparable metric of pavement life extension for both treated and untreated projects. Life 70 is simply a measure of how long a pavement will take to reach a Segment Rating of 70 given the Segment Rating at its start.

In order to calculate the Life 70 of segments, for each segment, all consecutive Segment Ratings were plotted against time as depicted in

Figure 26. The year the survey was conducted was plotted on the x-axis while the Segment Rating was plotted along the y-axis.

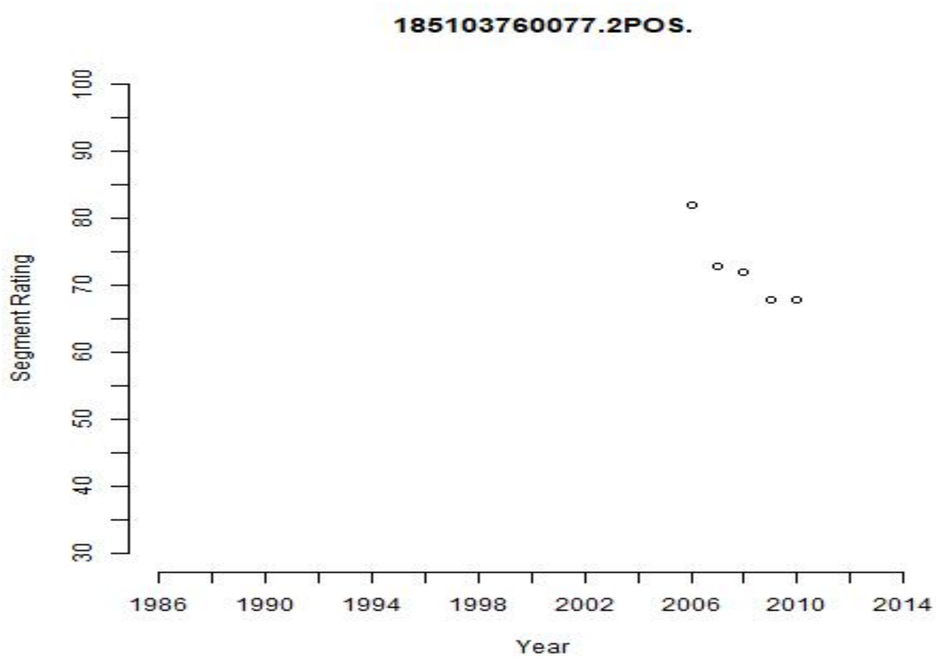

Figure 26. Plot of Segment Ratings over time

After plotting the pavement ratings over time, in order to calculate the Life 70 of each segment the following assumptions had to be made:

a. The assumed deterioration trend for both crack sealed and non-crack sealed segments is linear.
b. The minimum number of consecutive years' worth of data needed to properly predict Life 70 is 4 consecutive years.
c. The minimum acceptable R^2 value for a linear trend needed to properly predict the Life 70 has to be greater than 0.50.

Using these assumptions, a linear regression for each segment was calculated. The linear regression equation calculated was then used to predict the number of years from the Start Year until that segment reached a Segment Rating of 70. The number of years to 70 (Life 70) and the Start Year for each segment were recorded as well as whether the segment had received crack sealing or not.

The Life 70 for all segments with the same Start Year Segment Rating that had received an application of crack sealing was aggregated and averaged; similarly, the average Life 70 was calculated for each Start Year Segment Rating for non-treated segments. Segment selection was only limited by the assumptions made previously; no additional criteria was imposed. Once the average Life 70 for each Start Year rating was calculated for both groups (treated and non-treated), the difference between the two was calculated. The difference in this case refers to the difference between the treated average Life 70 and the non-treated average Life 70. The results of the aggregation are displayed in

Table 19 below. Subsequently, the difference in average Life 70 was plotted with the corresponding Start Year Segment Rating as shown in

Figure 27.

Table 19. Summary of average Life 70

Start Year Segment Rating	Crack Sealed Segments		Non-Crack Sealed Segments		Difference Between Average Life 70
	Average Life 70	*Number of Segments*	*Average Life 70*	*Number of Segments*	
76	2.475967	17	2.423978	77	0.051989
77	3.004614	14	2.103753	98	0.900862
78	2.745248	18	2.908545	71	-0.1633
79	3.637867	24	3.164315	81	0.473552
80	3.535969	49	3.333195	130	0.202774
81	5.072301	18	3.360846	85	1.711455
82	3.006511	22	3.738865	84	-0.73235
83	3.602027	24	4.320829	137	-0.7188
84	6.866852	10	3.847469	56	3.019383
85	3.641438	12	3.9222	96	-0.28076
86	4.49717	11	4.096868	49	0.400302
87	3.698084	12	3.839002	46	-0.14092
88	4.723546	18	4.179996	84	0.54355
89	5.780759	8	4.36776	54	1.412999
90	4.202028	8	5.271723	84	-1.0697
91	2.948234	4	5.151343	37	-2.20311
92	4.915505	17	5.21754	83	-0.30203
93	4.145581	3	5.134856	13	-0.98928
94	9.932698	4	5.448068	44	4.48463
95	NaN	0	6.858574	21	NaN
96	2.177419	1	4.500228	15	-2.32281
97	NaN	0	8.748979	4	NaN
98	4.240808	6	5.055594	12	-0.81479
99	3.527397	1	3.833333	1	-0.30594
100	3.925403	2	9.346974	6	-5.42157

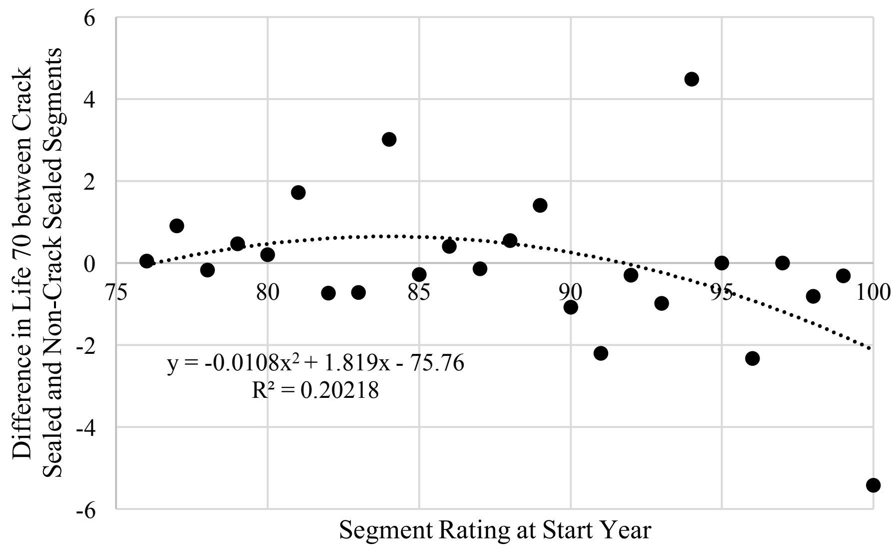

Figure 27. Difference in Life 70 at differing Start Year ratings

The plotted data as depicted in **Figure 27** shows a weak trend between the difference in Life 70 and the Segment Rating at the Start Year. Using the coefficient of determination as a metric of good fit, a 2nd degree polynomial line was found to be the best fit for the data depicted resulting in an R^2 of 0.2022. Under this model, the optimal timing for crack seal application was able to be calculated using optimization. The equation below shows the optimization process using the polynomial equation determined to be of best fit. The resulting optimization leads to the conclusion that the best timing for crack seal application, where the Life 70 is maximized when compared to a non-treated segment, is at a Segment Rating of 84.

$$y = -0.0108x^2 + 1.819x - 75.76 \tag{2}$$

$$y' = \frac{dy}{dx}(-0.0108x^2 + 1.819x - 75.76) = 0$$

$$-0.0216x + 1.819 = 0$$

$$x = 84.21$$

4.2.4.4 Limitations of Results

As stated throughout both Section 4.3 and this section, the biggest limitation of data analysis at a network or segment level is the quality of the data provided in COPACES. As seen through the data processing procedure, the number of observations in the raw data set was greatly diminished following the processing procedure. The quality of the processed data also limited the analysis of the crack sealing performance. In particular, for many segments, the survey results from year to year varied greatly. While studies have shown the typical trend of pavement is a deterioration in the pavement condition each year, much of the data at the segment level did not follow this trend and instead the Segment Ratings varied in direction and point value each year. This randomness and lack of consistency can be attributed to the way in which segment-level data is collected, where one 100-feet part of a segment length is analyzed each year. While the part of roadway should be a representative sample of the whole segment, there is room for error by the human surveyor which then results in variability in the segment deterioration trend and therefore pavement performance.

CHAPTER 5. ANALYSIS OF MULTI-YEAR PAVEMENT PERFORMANCE AND MR&R NEEDS FOR STATE FUNDING

The balance between meeting federal and state performance guidelines and keeping the pavement maintenance and rehabilitation budget to a level that is accepted by the state legislature is a difficult process. Often times, the balance is unachievable as the cost to keep pavement performing at even the minimum performance standard is unable to be met by the funding provided by the state and federal government. Such a restriction can result in poor pavement MR&R planning which focuses on a "worst-first" approach rather than a more sustainable method. The goal of this chapter is to focus on the underlying system of funding and performance metrics in the state of Georgia, how the developed pavement forecasting model can be used as a tool to advocate for funding levels or to understand the predicted network performance when that funding cannot be met, and provide suggestions on how the tool can be used to implement further funding and policy strategies that are best for the network. In doing so, the hope is to provide higher-level management within department of transportation evidence and support for decision-making for pavement management activities.

5.1 Federal-Level Funding and Performance Criteria for MR&R

Federal-level funding and governance for MR&R and transportation in general is provided through a combination of federal entities (such as the Federal Highway Administration) and the United States Congress. These two players are key to developing state apportionments and federal guidelines to ensure roadways in the NHS are appropriately improved and maintained as the system ages. In terms of pavement maintenance, the federal government's emphasis is on regulation of the performance goals rather than providing all necessary funding. The following sections will provide detail on the method and means for funding provided to the states from the federal government as well as the performance measures required at a state level to receive any funding.

5.1.1 Funding

Funding streams from the federal government are dictated by 23 U.S. Code § 104 or the MAP-21 Act which lays out the rules of apportionment. Since 2012, apportionment has utilized a formula-based approach to provide funding for state departments of transportation. Under 23 U.S. Code § 104, apportionment to states must fall under a) the National Highway Performance Program (NHHP), b) the Surface Transportation Block Grant Program (STBG), c) the Highway Safety Improvement Program (HSIP), d) the Congestion Mitigation and Air Quality Improvement Program (CMAQ), e) Metropolitan Planning, or f) the National Highway Freight Program (NHFP). In the case of routine and capital maintenance, funding streams from a federal level fall under the NHHP which enables "construction, reconstruction, resurfacing, restoration, rehabilitation, preservation, or operational improvement of segments of the National Highway System" (23 U.S.C 104, 2012). Under this Code, states receive funding which is equivalent to the national amount for the program for a fiscal year multiplied by the ratio of the state's base apportionment for the fiscal year (which is the same a previous year) over the total national base apportionment. The total state funding is subdivided into the six programs previously described. Of the total apportionment, a

63.7 percent deduct funding for freight and congestion programs is assigned to the NHHP and consequently, can be used by the state (23 U.S.C 104, 2012). In the state of Georgia, under these provisions, the Department of Transportation received a total of $1,593,146,310 from the federal government of which only $285,486,452 was used on MR&R in FY 2017 (Deal & MacCartney, 2017).

5.1.2 Policy on Minimum Performance

Under MAP-21, funding is to be dispersed to state agencies upon satisfaction of minimum performance and condition requirements. When specifically looking at pavements, states are required to develop risk-based asset management plans that summarize the assets and their conditions, inform the FHWA of the objectives and measures used by the state, identify any performance gaps, report life cycle cost and risk analyses, determine a financial plan, and disclose investment strategies (23 U.S.C 119, 2012). The policy requires that the state maintains highway infrastructure in a state of good repair by measuring the condition and performance of the interstate systems that fall within a state as well as the condition and performance of non-interstate roadways in the NHS (23 U.S.C 150, 2012). Both MAP-21 and the FAST Act determine that failure to meet these goals alters the funding received by the state. According to Section 119, states that fail to comply are forced to match federal apportionment from the previous year and utilize at least ten percent of the federal funds apportionment for the current Fiscal Year for the purpose of maintenance. Compliance to the minimum standards is to occur every two years under the FAST Act and is evaluated by the Secretary of Transportation. Under Federal Register 490.307, the measures used in the decision are percent of pavements in good condition on the interstate system, percent of pavements in poor condition on the interstate system, percent of pavements in the NHS that are not interstates in good condition, and percent of pavements in the NHS that are not interstates in poor condition (23 U.S.C 490, 2016). While the condition states of good and poor are left to states to decide, each state is additionally required to report condition in terms of IRI, PSR, rutting, crack percentage, and thickness flexibility (FHWA, 2016). The exact percentage allowed in each condition has not been determined yet, but it is suspected the targets will be set May 20, 2018 following the first reporting of four year performance by the states (FHWA, 2017b).

5.2 State-Level Funding and Performance Criteria for MR&R

Whereas the federal level of government provides extensive policy on performance criteria for pavement networks, the state-level government is important in funding MR&R on state and federally owned roadways. Funding at a state level is dictated by the state legislature while additional performance objectives for pavements are created by the state department of transportation. In this section, the funding and performance policies for pavement management are more thoroughly explored for the state of Georgia.

5.2.1 Funding

In the state of Georgia, routine maintenance is largely funded using a combination of motor fuel tax, hotel fees, electric vehicle fees, heavy vehicle fees, bridge bonds, and other fees imposed by the state. These taxes and fees, which are collected at a local level, are utilized to create a budget for the GDOT which is created and voted on by the Governor and the Georgia General Assembly each Fiscal Year. In FY 2017, state funding allotted $2.06 billion dollars to the state DOT, approximately 25% more funding than that provided by the federal government. Of the $2.06 billion dollars, it is estimated that approximately $402 million of that was used for interstate maintenance and resurfacing and state route resurfacing in FY 2017 (GDOT, 2017a). The difference between the total budget of the GDOT and that received for MR&R specifically leaves room for further budget allocation to MR&R. Through better forecasting of pavement performance, the aim is to better emphasize the role additional funding plays on the pavement network.

5.2.2 Policy on Minimum Performance

While compliance to federal performance standards is the primary state goal, the Georgia Department of Transportation sets separate performance goals to conform to their strategic goal of taking care of existing assets. For pavement, the goal for minimum performance for non-interstate roads is to maintain 90% or more of roadways at a COPACES value of 71 or higher. Similarly, the GDOT also sets the same goal for interstate pavements. In FY 2017, 74% of the GDOT maintained interstates and 71% of the GDOT maintained non-interstates met the target COPACES value (GDOT, 2017b). While existing goals for performance are set based on network conditions, in the future, pavement performance goals will incorporate pavement route priority. Through this approach, Critical, High, Medium, and Low priority routes can have separate performance goals based on their importance. Implications of this strategy are discussed in the next section.

5.3 Funding Needs Using Pavement Performance Analyses

In this section, the newly updated model described in Chapter 3 will be utilized for a series of analyses focused on forecasting pavement performance and MR&R needs in both the short and long-term. The model, which enables both customization and optimization, will be implemented in understanding two scenarios: network-level performance with a fixed funding stream and network-level funding with fixed performance goals. In both cases, the model can be utilized to support decision-making and legislative funding recommendations for MR&R activities within Georgia. In doing so, the hope is to enable more efficient expenditure while complying with state and federal performance measures.

5.3.1 Network-Level Performance with Existing Funding Levels

The first scenario explored is focused on understanding what the pavement condition in the network would look like if funding levels remained the same. In this case, the funding level from FY 2017 of $448 million, the most recently reported year of funding, was used as the funding level for each year in the analysis. The results of this scenario are reported for both the short-term (5 years) and the long-term (10 years), and the allocation of funding to each pavement "family" is discussed. For both strategies, it is assumed that the $448 million be split evenly between the between Critical, High, Medium, and Low categories for interstate and non-interstates (5 categories total), resulting in each category receiving $89.6 million annually.

5.3.1.1 Short-Term Performance

Short-term performance of the network using the existing budget is the first case simulated. In this scenario, the current budget is applied annually for five years where the budget can be distributed equally by either mileage or by working district. For the purpose of both performance case studies, budget per Critical, High, Medium, and Low categories are evenly distributed by mileage rather than district as the network-level performance using distribution by mileage rather than distribution by district is slightly better. At the end of five years, the network composite score of the former is 81.50 while the composite score of the latter is 80.84 when optimizing on each family. To analyze short-term performance, two optimization strategies were considered: Optimization on Each Family and Optimization on all Families.

Optimization on Each Family uses the optimization strategy to maximize performance for each of the 35 created families discussed in previous sections. The results of this analysis are presented in **Figure 28-Figure 30.**

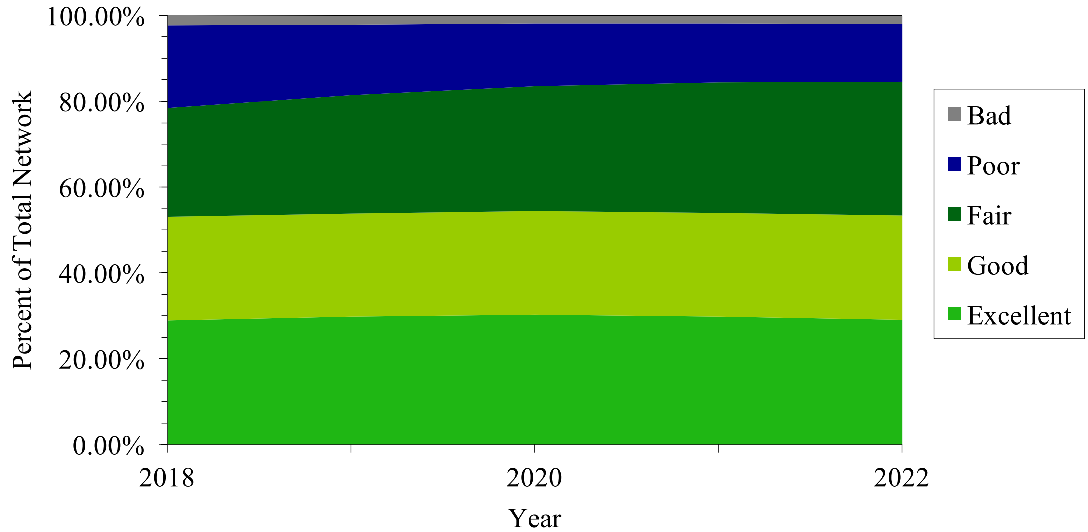

Figure 28. Yearly condition distribution for short-term performance Optimization on Each Family

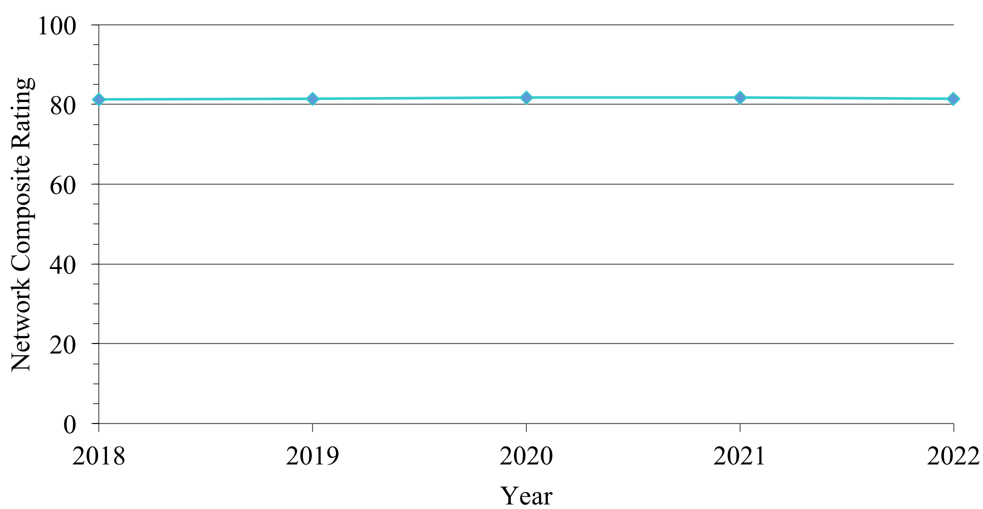

Figure 29. Network composite rating for short-term performance Optimization on Each Family

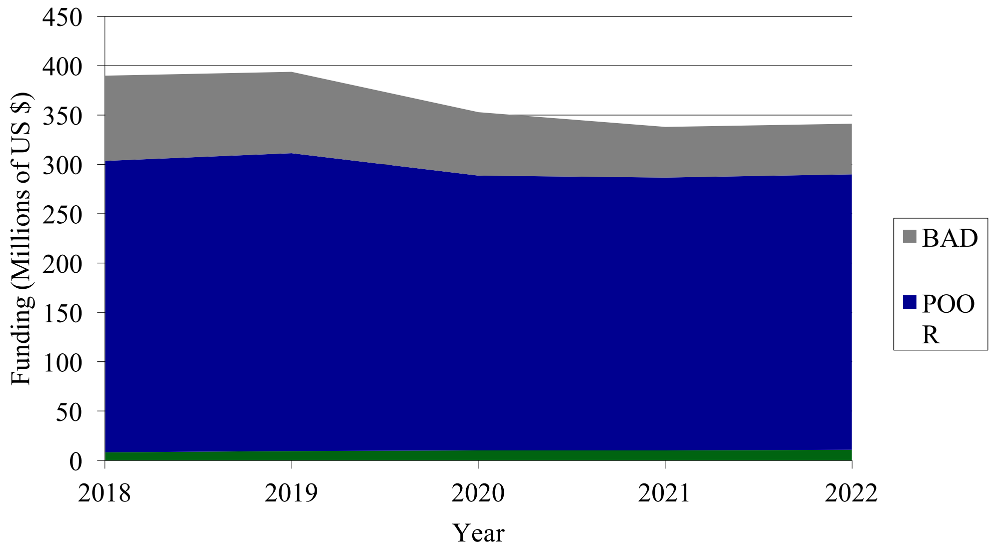

Figure 30. Detail cost distribution per year for short-term performance Optimization on Each Family

Optimization on All Families refers to optimization on the entire network rather than on an individual family level. The results of this analysis are presented in **Figure 31-Figure 33.**

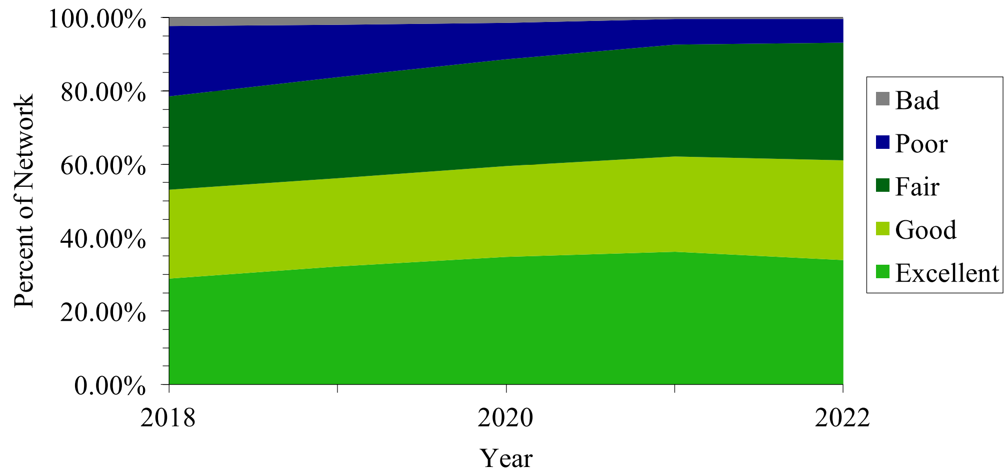

Figure 31. Yearly condition distribution for short-term performance Optimization on All Families

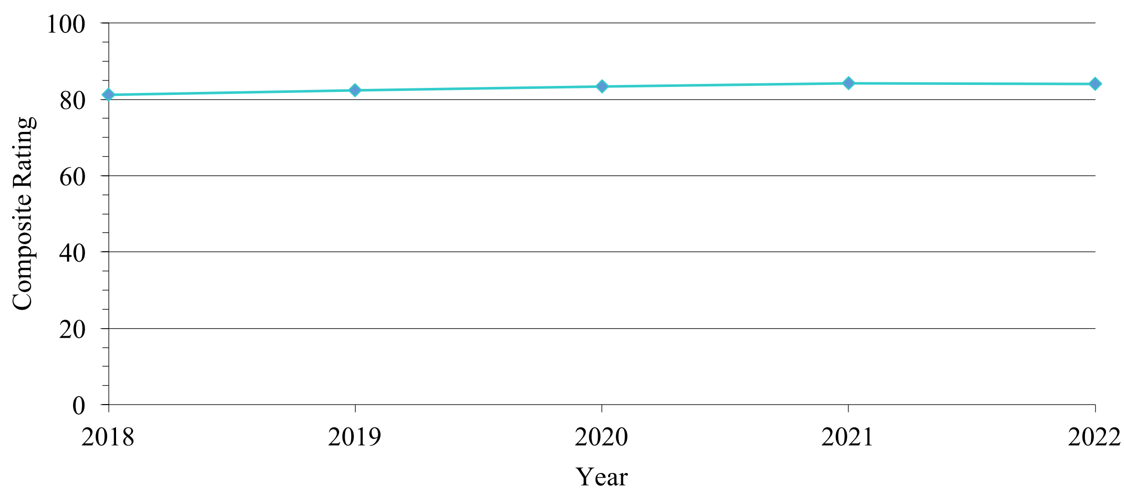

Figure 32. Network composite rating for short-term performance Optimization on All Families

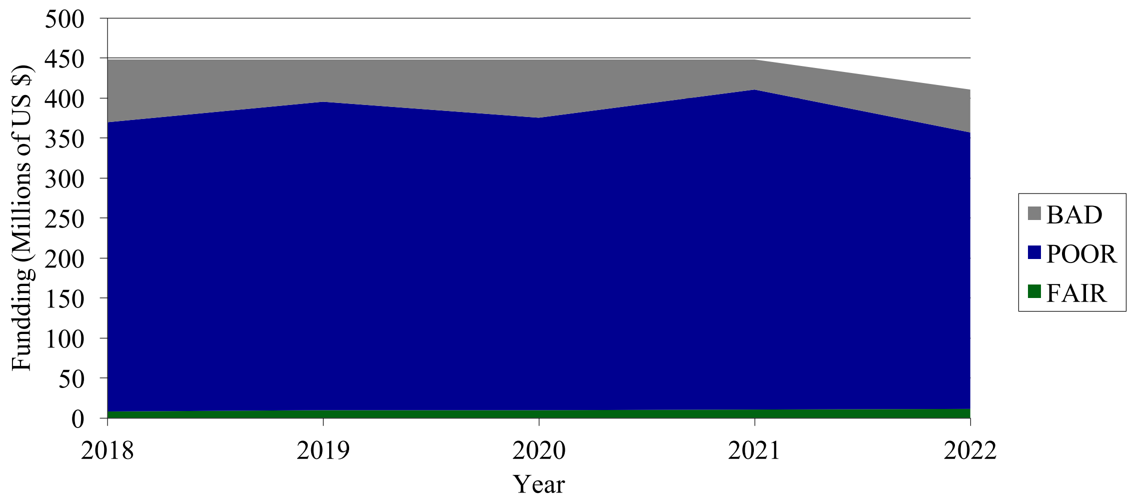

Figure 33. Detail cost distribution per year for short-term performance Optimization on All Families

Comparing the two optimization strategies in the short-term, the most distinct difference can be seen in regards to cost of each optimization strategy. While optimizing on each family results in less than the full $448 million spent annually, Optimization on All Families utilized the total budget for the first four years. In fact, the average yearly expenditure for Optimization on Each Family was $363 million while the average yearly expenditure for Optimization on All Families was $441 million. The discrepancy in yearly cost of these two strategies is a result of all pavement families not being of equal value or cost. While each family may be optimized, the system overall will not be performing as well as it can. One family may meet the threshold of a composite score of 80 while the other families are not. The effect these two optimization strategies have on performance is supported by the composite rating calculated for the network each year. Optimization on Each Family resulted in a composite rating of 81.50 after five years whereas optimization on the network resulted in composite rating of 84.05 at the end of five years.

5.3.1.2 <u>Long-Term Performance</u>

Long-term performance of the network using the existing budget is the second case simulated. In this scenario, the current budget is applied annually for 10 years in the future where budget can be distributed equally by either mileage or by working district. For the purpose of both performance case studies, once again, budgets per Critical, High, Medium, and Low categories are evenly distributed by mileage rather than by district as the network performance using distribution by mileage rather than distribution by district is slightly better. At the end of ten years, the network composite score of the former is while 80.73 the composite score of the latter is 79.38 when optimizing on each family. To analyze long-term performance, two optimization strategies were considered: Optimization on Each Family and Optimization on All Families.

Optimization on Each Family uses the optimization strategy to maximize performance for each of the 35 created families discussed in previous sections. The results of this analysis are presented in **Figure 34-Figure 36.**

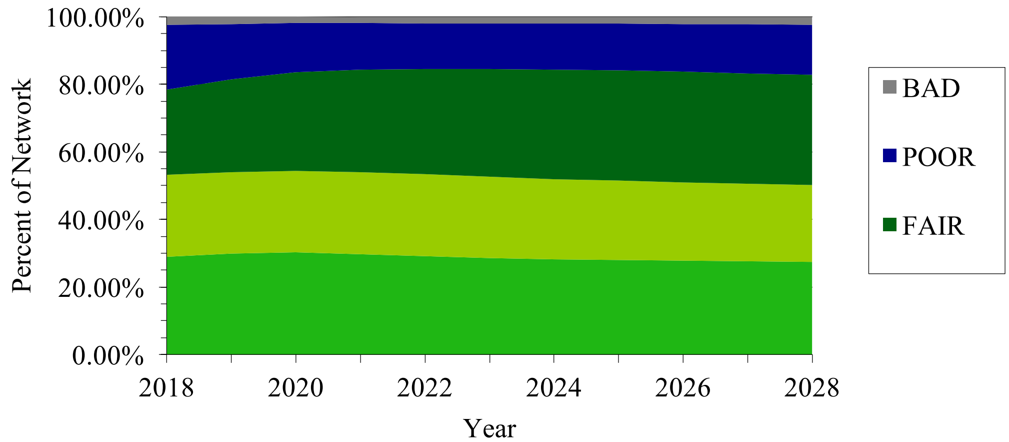

Figure 34. Yearly condition distribution for long-term performance Optimization on Each Family

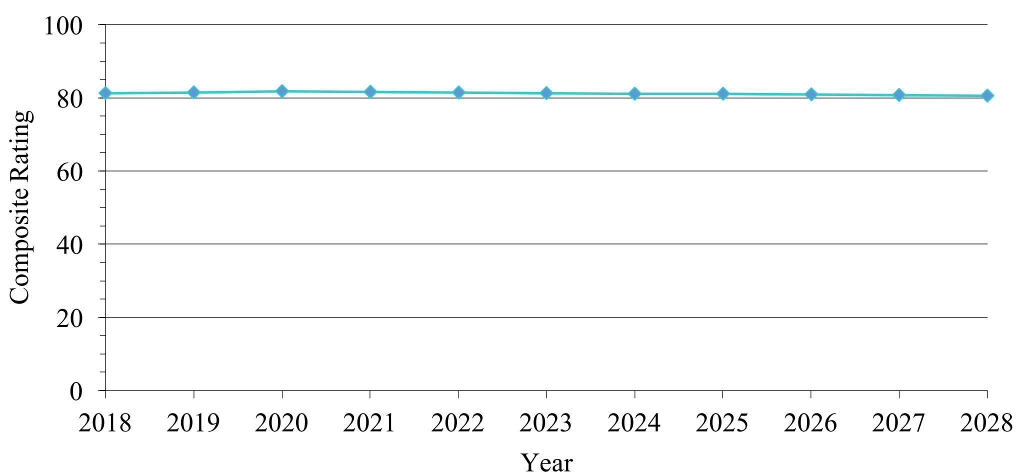

Figure 35. Network composite rating for long-term performance Optimization on Each Family

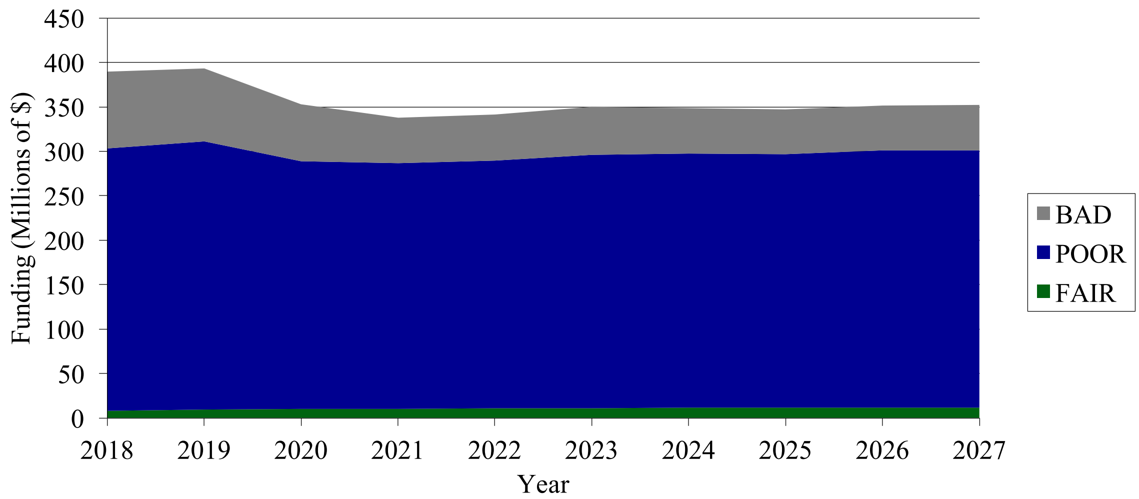

Figure 36. Detail cost distribution per year for long-term performance Optimization on Each Family

Optimization on All Families refers to optimization on the entire network rather than on an individual family. The results of this analysis are presented in **Figure 37-Figure 39.**

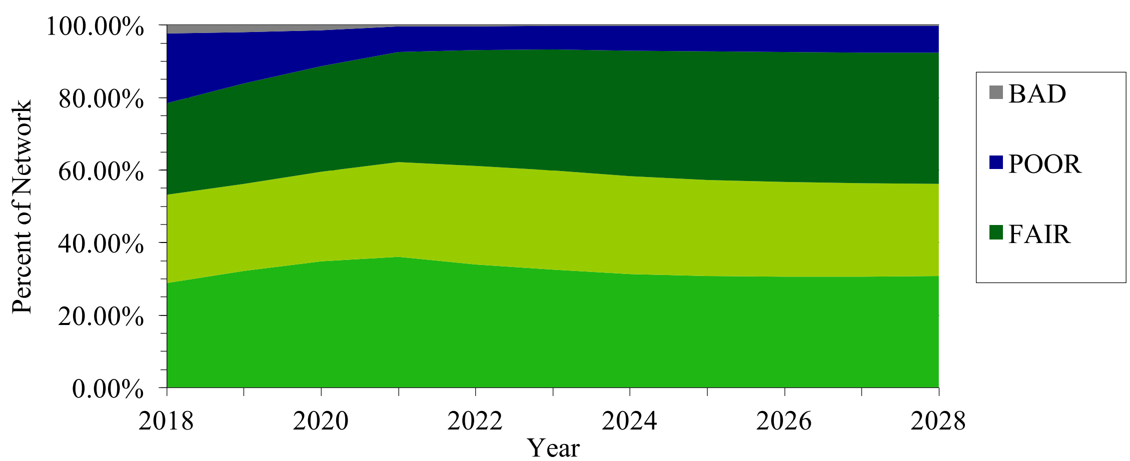

Figure 37. Yearly condition distribution for long-term performance Optimization on All Families

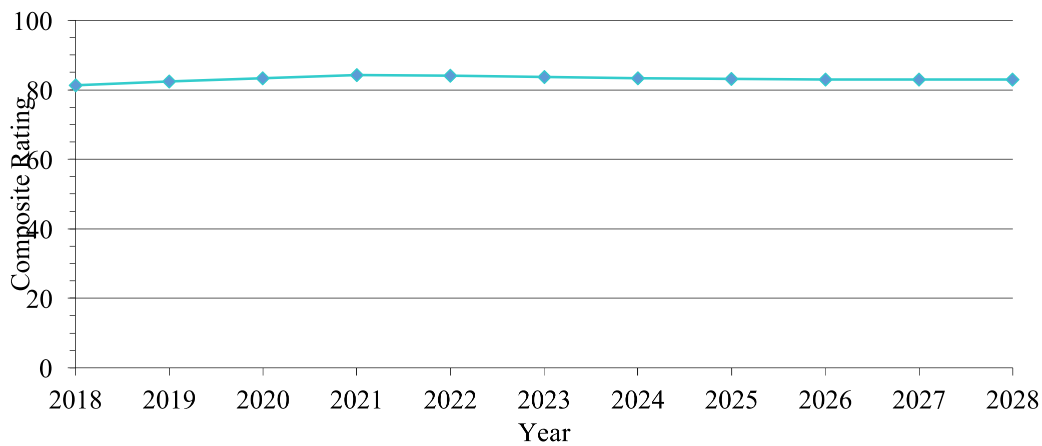

Figure 38. Network composite rating for long-term performance Optimization on All Families

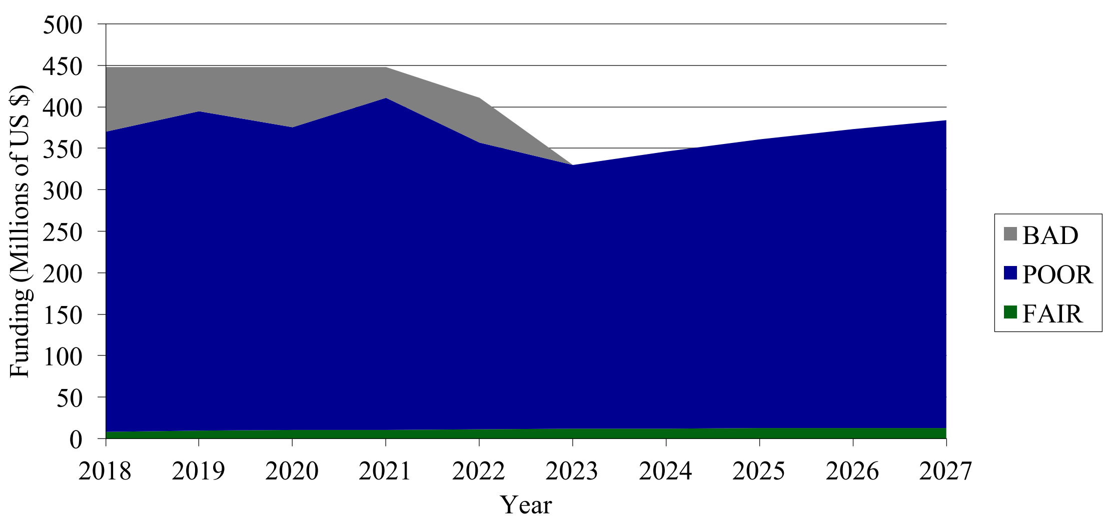

Figure 39. Detail cost distribution per year for long-term performance Optimization on All Families

Comparing the two optimization strategies in the long-term yields similar results to that of the short-term. While optimizing on each family results in less than the full $448 million budget being spent annually, Optimization on All Families utilized the total budget each year for the first four years. In fact, the average yearly expenditure for Optimization on Each Family was $357 million while Optimization on All Families utilized an average of $400 million dollars. Optimization on Each Family resulted in a composite rating of 80.73 after ten years whereas optimization on the network resulted in composite rating of 82.94 at the end of ten years. These composite ratings are generally lower than after a five-year analysis period due to the increasing cost of construction that is more evident over a ten-year analysis period.

5.3.2 Network-Level Funding with Defined Performance Goals

In a different scenario, a what-if analysis is conducted using the updated model. The analysis is focused on determining the amount of funding necessary for achieving minimum performance goals based on each state route priority category and overall. The scenario will focus on situations that achieve certain condition performance goals which are further described in subsequent subsections.

5.3.2.1 <u>Minimum Funding Required to Achieve All Performance Goals</u>

The first case study using Need Analysis is focused on achieving determined composite scores based on the state route priority of the roadways. While there is no set policy as to how the pavements in each category must be performing, using engineering judgement, composite ratings for each category were selected as depicted in **Table 20.** The logic behind the values chosen is that higher priority state routes would require higher performance as these groups of roadways represent sources of economic benefit. While these roadways require higher performance, the lower priority roadways are not neglected in this scenario, with the lowest value used being a composite rating of 68 which is well above a truly failing system with a composite rating of 50.

Table 20. Minimum composite ratings for Need Analysis based on priority

Priority Category	Non-interstate Minimum Composite Score	Interstate Minimum Composite Score
Critical	85	85
High	82	N/A
Medium	72	N/A
Low	68	N/A

Using these inputs, the model is able output the funding need to maintain the system in the conditions described. The results of the analysis over a ten-year period are depicted in

Figure 40-

Figure 42**.** From the figures, it is evident that while the initial costs to maintain the network to these standards are low with expenditure in subsequent years is increasing. The average annual expenditure on MR&R for the ten years of analysis is only $134 million. Using the analysis scenario, the composite score fluctuates greatly peaking at 94 for the network and ending at a composite rating of 77.3. The low composite rating for the network in the long-term suggests that alternative performance goals that are higher for each category of pavements be considered.

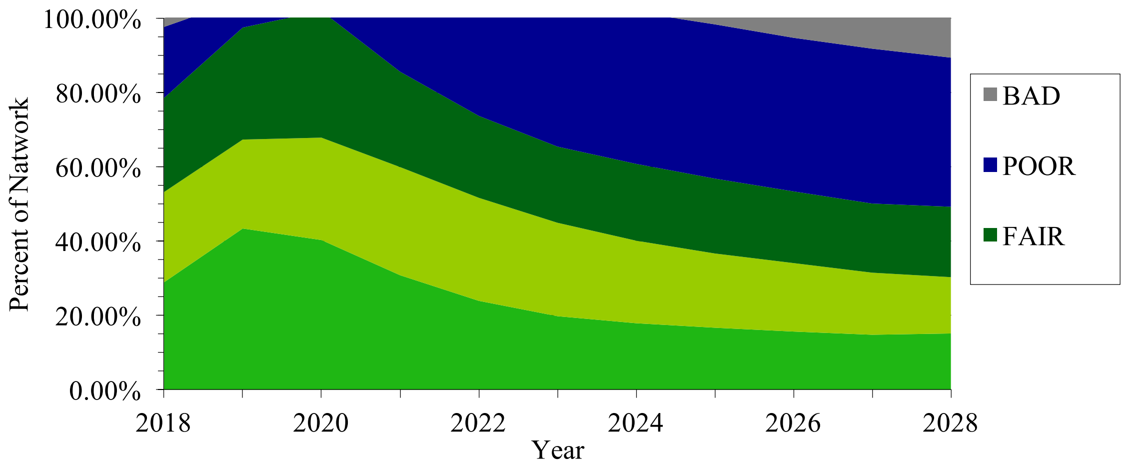

Figure 40. Yearly condition distribution for long-term Need Analysis for Each Priority Category

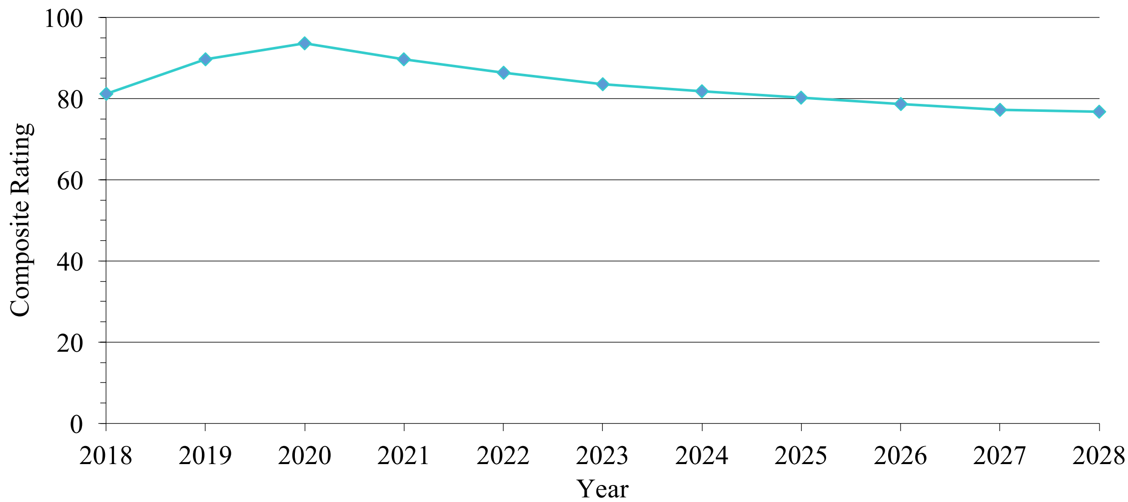

Figure 41. Network composite rating for long-term Need Analysis for Each Priority Category

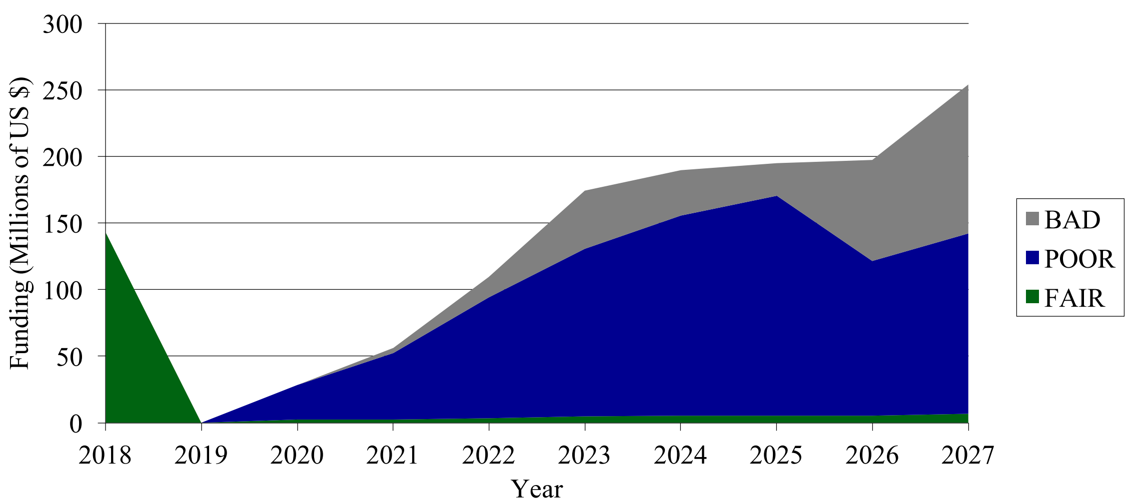

Figure 42. Detail cost distribution per year for long-term Need Analysis for Each Priority Category

5.3.2.2 Minimum Funding Required to Achieve Goals for Entire System

According to state policy, a minimum performance of 71 is required for both interstate and non-interstate routes. The focus of this section is to carry out an analysis that determines the level of funding necessary to achieve this goal as well as the suggested state goal of a composite rating of greater than or equal to 85 with the sum of Poor or Bad pavement mileage less than or equal to 10%.

In the first scenario, a Need Analysis is conducted constraining the system to a composite rating greater than 71 and the sum of Poor or Bad pavements being equal to 10%. Upon running the analysis, it is evident that the state policy is a very low target for pavements within the state of Georgia. To meet the performance goal over a ten-year period, an average of $347 million has to be expended each year. However, the approach does not represent a sustainable MR&R strategy as the strategy emphasizes treating pavements which require Major Rehabilitation or Major Preventative Maintenance over routine maintenance.

Figure 43-

Figure 45 depict the details of the first case.

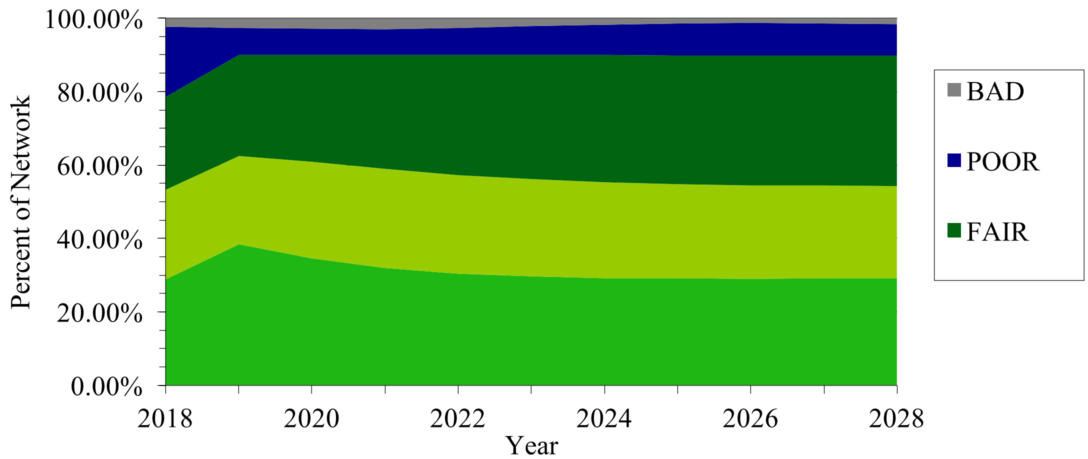

Figure 43. Yearly condition distribution for long-term Need Analysis for state performance standards

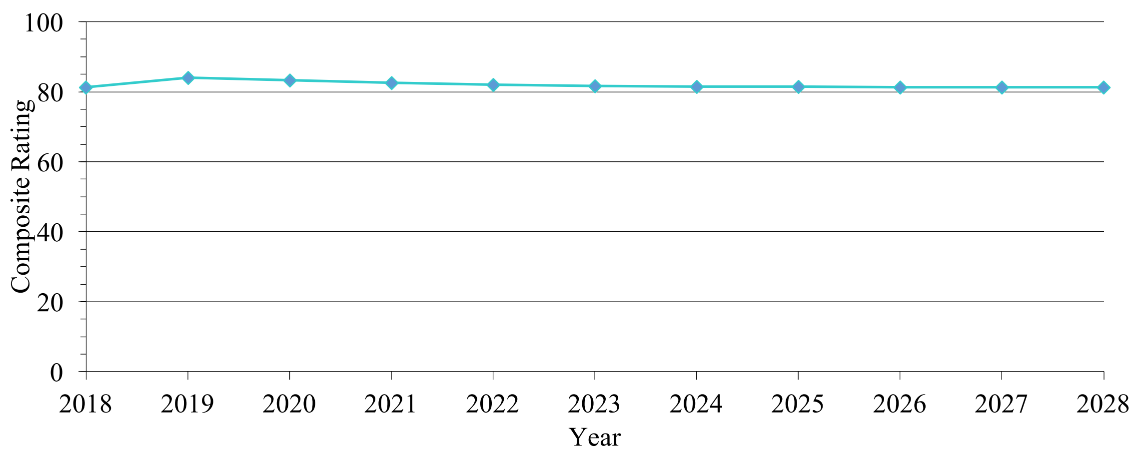

Figure 44. Network composite rating for long-term Need Analysis for state performance standards

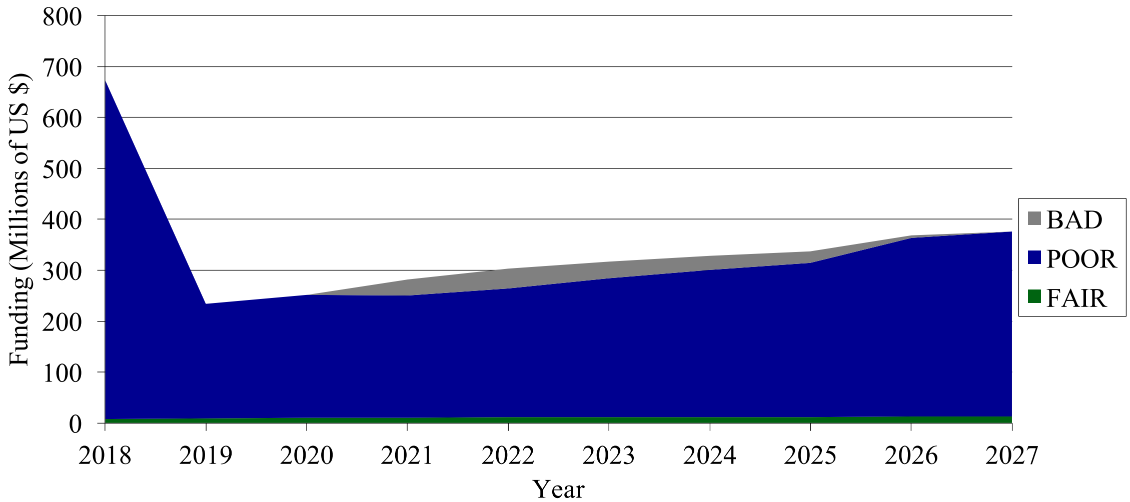

Figure 45. Detail cost distribution per year for long-term Need Analysis for state performance standards

The next scenario analyzed was the use of the suggested state performance standards to define the need over a ten-year period. The suggested policy is focused on achieving a composite rating of 85 or great with less than 10 percent of total pavements in Poor or Bad condition. The analysis resulted in considerable spending initially to meet these performance constraints. For the first year of the analysis, $763 million was required to achieve the performance goal. However, subsequent years require significantly less investment in MR&R with an average budget of $351 million per year. The approach was similar to that conducted in the previous Need Analysis where performance was set for each priority level. However, this strategy resulted in a more stable composite score.

Figure 46-

Figure 48 show the trends of performance and expenditure over the ten-year analysis period.

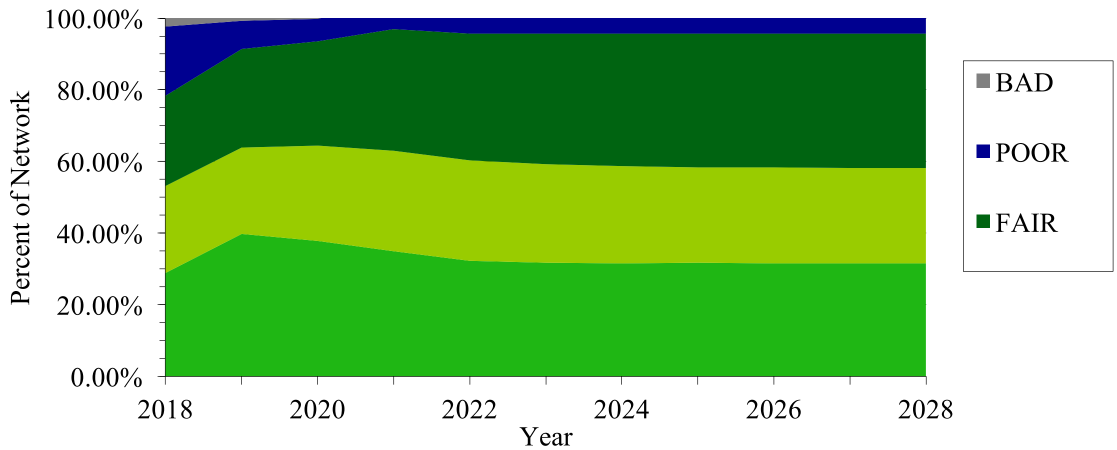

Figure 46. Yearly condition distribution for long-term Need Analysis for suggested state performance standards

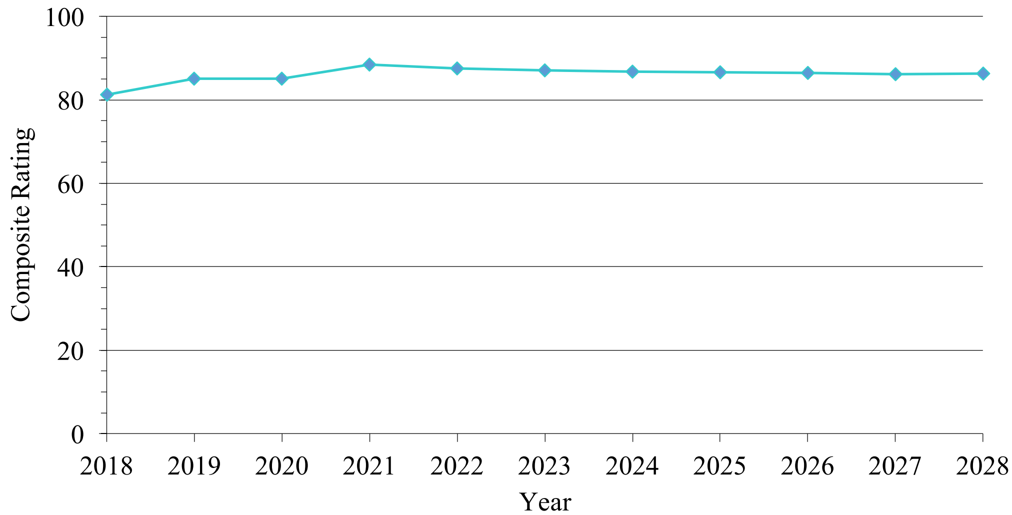

Figure 47. Network composite rating for long-term Need Analysis for suggested state performance standards

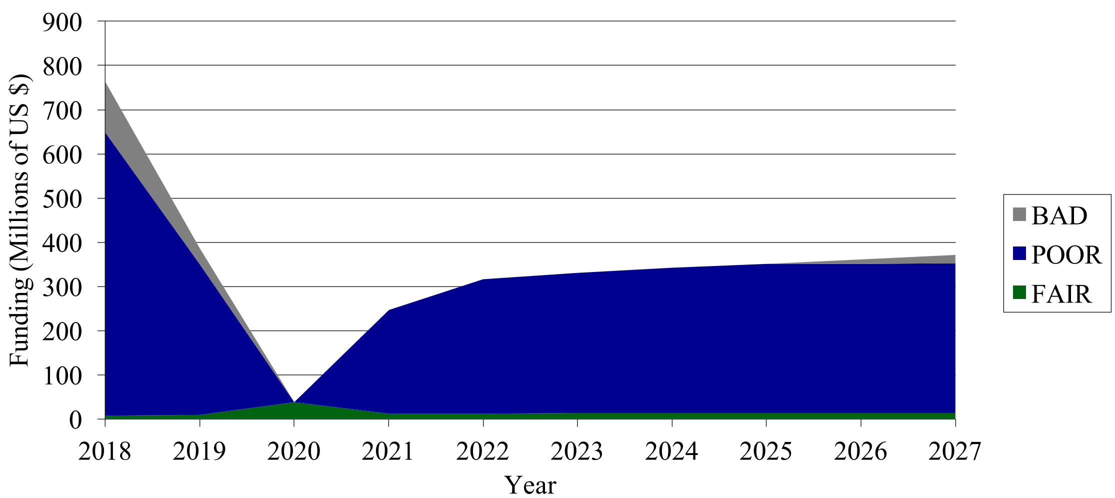

Figure 48. Detail cost distribution per year for long-term Need Analysis for suggested state performance standard

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

The thesis of this report was to update and perform analyses that predict pavement deterioration and MR&R expenditure costs within the state of Georgia. By doing so, the aim was to create a better tool to assist the GDOT in high-level decision-making activities satisfying requirements of federal and state policy. This section aims to summarize the changes made to improve the PMS used by the GDOT.

6.1 Summary of Contributions

The four primary goals of this research were to introduce the use of state route priority as a feature for deterioration modeling and analysis, to conduct a literature review on the current practices in deterioration modeling, to create a systematic approach for processing and utilizing expenditure data for the purpose of cost modeling, to analyze the trigger criteria for MR&R treatments, and to run analyses that support state decision-making on MR&R expenditures.

In Chapters 2 and 3, definitions and implementation strategies to update the existing PMS model were explored. An extensive literature review on pavement deterioration modeling revealed that while other methods may be adequate for modeling pavement deterioration, a Markovian approach is still recommended for use by the Georgia Department of Transportation. Use of state route priority categories to create pavement families resulted in the creation of 35 pavement families and subsequently 35 Markov Transition Probability Matrices (TPMs). The use of state route priority in addition to working district and interstate versus non-interstate classification enabled better grouping of pavement projects with similar attributes and therefore, similar pavement deterioration trends. The introduction of more MR&R expenditure data enabled unit costs for Major and Minor Preventative Maintenance and Major Rehabilitation activities to be determined. The resulting unit costs used in the model were $225,083, $2,577, and $316,321 per centerline mile respectively for non-interstates, and $885,605, $12,652, and $1,265,150 per centerline mile for interstates. The data was also used to determine the annual average escalation cost (AAEC) of 1.79% per year.

In Chapter 4, trigger criteria for crack sealing was discussed. A data processing procedure was put in place to remove segment-level data with missing information and duplicates. Using the methodology established, the number of raw entries was reduced from 562,648 to 455,342. Through a preliminary overview study of crack sealing projects, it was found within the state the average Segment Rating before the application of crack sealing was 69.75. The mean number of years in a row that crack sealing was observed was 2.087 years. Additionally, using a difference in means between crack sealed and non-crack sealed projects, the Life 70 of a segment was found to be optimized when crack sealing was applied to segment at Segment Rating of 84.

Chapter 5 discussed potential strategies to meet both performance and budget goals for MR&R activities using the updated model. In the short-term, analysis of pavement performance using the existing budget of $448 million a year was conducted. Optimization on Each Family resulted in a composite rating of 81.50 after five years whereas optimization on the network resulted in composite rating of 84.05 at the end of five years. Optimization on Each Family resulted in an annual expenditure averaging

$363 million rather than the full $448 million. In the long-term analysis of pavement performance using the existing budget of $448 million a year, Optimization on Each Family resulted in a composite rating of 80.73 after ten years whereas optimization on the network resulted in composite rating of 82.94 at the end of ten years. The average yearly expenditure for Optimization on Each Family was $357 million while Optimization on All Families utilized an average of $400 million a year. A need analysis was conducted to determine minimum funding to achieve a composite rating of 85 for Critical interstate and non-interstate projects, a composite score of 82 for High priority projects, a composite score of 72 for Medium priority projects, and a composite score of 68 for Low priority projects. The average annual expenditure on MR&R for the ten years of analysis was only $134 million. Using this analysis scenario, the composite score fluctuates greatly peaking at 94 for the network and ending with a composite rating of 77.3. To achieve the state minimum performance standards, a composite score of 71 is required for both interstate and non-interstate routes. A Need Analysis reported only an average $347 million each year had to be expended for a ten-year period in this scenario. However, this worst-first approach, does not represent a sustainable MR&R strategy. Another scenario analyzed was focused on achieving a composite rating of 85 or better with less than 10 percent of total pavements in Poor or Bad condition. For the first year of the analysis, $763 million was required to achieve the performance goals. However, subsequent years require significantly less investment in MR&R with an average budget of $351 million per year.

6.2 Recommendations for Future Work

Despite the improvements made to the model, trigger criteria evaluation, and analyses to support decision-making, recommendations for improvement are provided. In terms of model development, a more systematic means of processing and evaluating data to be used in the model is recommended. The creation of an application that automatically cleans and outputs COPACES data for the creation of Transition Probability Matrices is suggested. Next, the evaluation of the usefulness of neural networks for the creation of a model should be studied more intensely. Through literature review, neural networks were found to be a viable means for modeling pavement deterioration in some states. A study of the usefulness of this modeling type on COPACES data is recommended. Additional a study on modeling of cost escalation is also recommended. While the existing model for cost used to support pavement preservation predictions provides a good base given the data provided, a more dynamic means of predicting escalation would be more suitable for accuracy in modeling. It is suggested that unit costs be evaluated on a more granular level. In the existing model, unit costs were calculated for Major and Minor Preventative Maintenance and Major Rehabilitation. A closer look at individual pavement preservation activities or treatment types for each of the pavement families could result in better future predictions.

To better support studies on pavement performance due to treatments, it is suggested that policy be introduced to ensure treatments other than crack sealing are properly reported in the survey logs. This would enable additional studies on trigger criteria for other MR&R treatments to be performed. To specifically improve data quality of crack sealing data, it is recommended that additional information be collected from the survey such as crack width and density. The collection of these additional variables can be used in a more thorough analysis of performance of crack sealing under certain conditions.

Finally, with regards to analyses used to support decision making, additional features should be incorporated into the existing decision-making tool to enable more refined or poignant analyses about the network to be conducted. Suggested additions include options to optimize based on state priority categories using both composite score and percent of pavements falling in the Poor and Bad state conditions. Input for additional needs from state legislators and policymakers within the state is recommended to ensure the effectiveness of the created model and analysis tool. The input would ensure the models are adequately providing information that is easy to understand and utilize.

APPENDIX A. PACES SURVEY DEDUCT VALUE ASSESSMENT CRITERIA

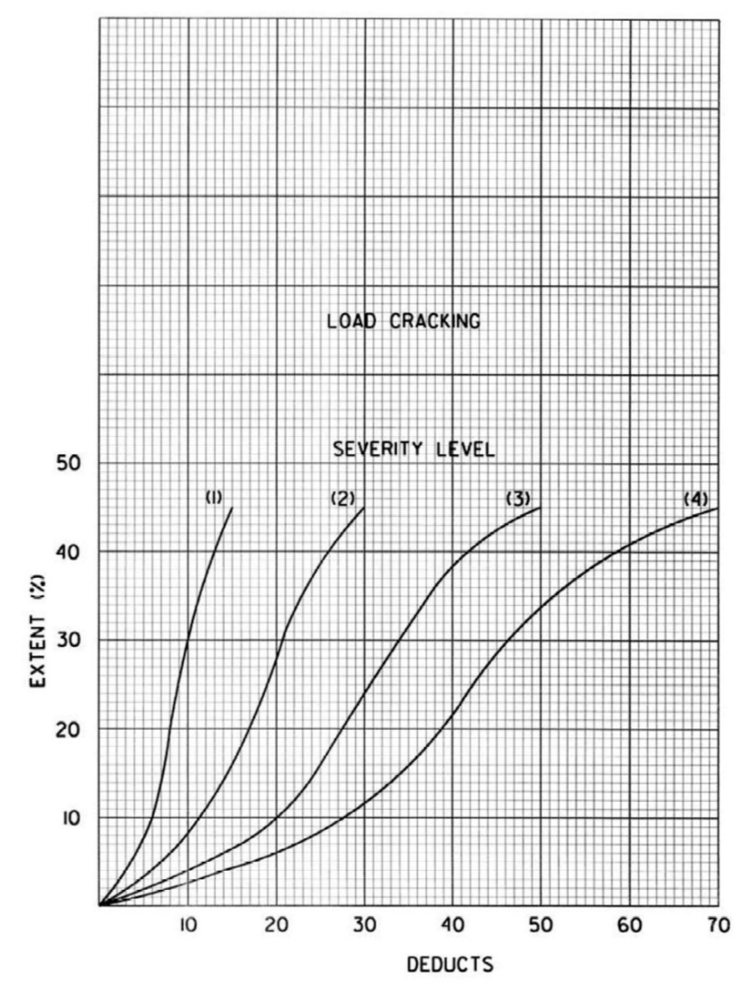

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Figure 49. Assessment criteria for load cracking deduct values (GDOT, 2007)

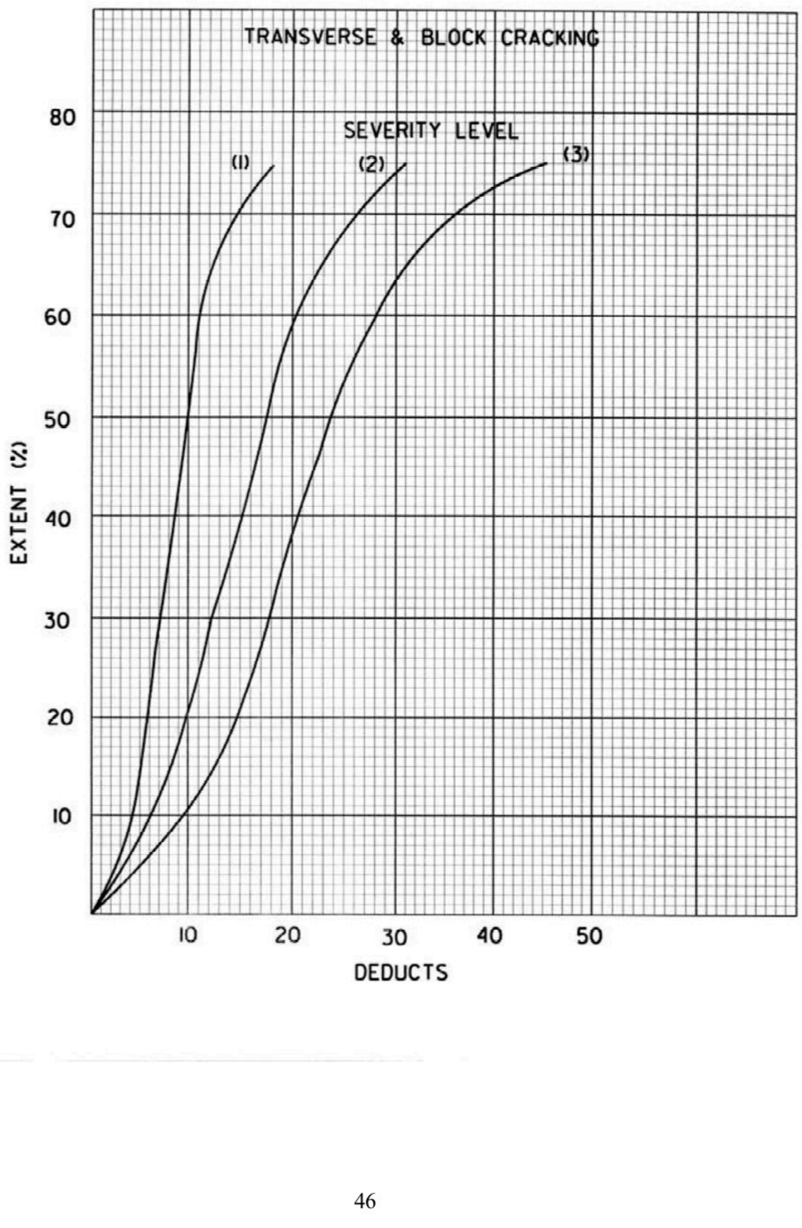

Figure 50. Assessment criteria for transverse and block cracking deduct values (GDOT, 2007)

Flexible Pavement Condition
Survey Deduct values

	Rutting Extent (inches)						
	0	1/8	1/4	3/8	1/2	5/8	3/4
Deducts	0	2	5	12	16	20	24

	Patches and Potholes Extent (# per mile)				
	1-2	3-6	7-10	11-15	>15
Deducts	2	5	10	17	25

		Corrugations/Pushing Extent (%)		
		1-10	11-25	>25
Severity	1	1	2	4
	2	2	4	7
	3	3	6	10

		Raveling Extent (%)					
		1-5	6-15	16-25	26-35	36-45	>45
Severity	1	2	5	6	8	10	13
	2	4	8	11	14	17	21
	3	6	12	16	20	25	30

		Edge Cracking Extent (%)			
		5-25	26-50	51-75	>75
Severity	1	1	2	3	4
	2	2	4	6	7
	3	3	6	8	10

		Loss of Pavement (%)			
		0-25	25-50	50-75	75-100
Severity	1	0	1	2	3
	2	2	4	6	8
	3	6	5	10	12

		Bleeding or Flushing Extent (%)		
		1-10	11-30	>30
Severity	1	2	5	8
	2	5	10	15

		Reflective Cracking (%)				
		5-15	16-30	31-45	46-50	>51
Severity	1	3	5	6	8	10
	2	6	8	11	14	20
	3	10	15	20	25	30

Figure 51. Other distress assessment criteria for deduct values (GDOT, 2007)

APPENDIX B. COPACES PROJECT FIELDS COLLECTED

Table 21. Project location field names

Field Name
STATUS
TRIPDATE
ROUTENO
ROUTESUFFIX
ROUTETYPE
PROJECTRATING
RATER
DISTRICT
OFFICE
COUNTYNO1
MILEPOSTFROM1
MILEPOSTTO1
COUNTYNO2
MILEPOSTFROM2
MILEPOSTTO2
COUNTYNO3
MILEPOSTFROM3
MILEPOSTTO3
AADT
STAA
PAVEMENTWIDTHMIN
PAVEMENTWIDTHMAX
PAVEMENTWIDTHTYP
SHOULDERWIDTHMIN
SHOULDERWIDTHMAX
SHOULDERWIDTHTYP
UNPAVEDSHOULDERWIDTH
DIVIDEDHIGHWAY
DIRECTION
NOBRIDGE
BRIDGEWIDTH
SURFACETYPE
CGMILLING
CGLENGTH

Table 21. Project location field names (Continued)

PROJECTREMARK
PROJECTLIMIT
FINALTREATMENT
ALLTREATMENT
TREATMENTVERSION
COST
PERCENTTRUCK
TREATYEAR
TREATMETHOD
NOOFLANE

Table 22. Project distress field names

Field Name
TRIPDATE
ROUTENO
RUT_AVG
RUT_DEDUCT
LOAD_SEV1_AVG
LOAD_SEV2_AVG
LOAD_SEV3_AVG
LOAD_SEV4_AVG
LOAD_SEV1_DEDUCT
LOAD_SEV2_DEDUCT
LOAD_SEV3_DEDUCT
LOAD_SEV4_DEDUCT
BLOCK_AVG
BLOCK_SEV
BLOCK_DEDUCT
REFLECT_AVG
REFLECT_SEV
REFLECT_DEDUCT
RAVEL_AVG
RAVEL_SEV
RAVEL_DEDUCT
EDGE_AVG
EDGE_SEV
EDGE_DEDUCT

Table 22. Project distress field names (Continued)

BLEED_AVG
BLEED_SEV
BLEED_DEDUCT
CORRUG_AVG
CORRUG_SEV
CORRUG_DEDUCT
LOSS_AVG
LOSS_SEV
LOSS_DEDUCT
SLOPE_AVG
SLOPE_DEDUCT
PATCH_AVG
PATCH_DEDUCT

APPENDIX C. NETWORK-LEVEL DATA PROCESSING

The following provides a more detailed procedure for the processing of the network-level data used for the creation of Markov TPMs. The COPACES information used is provided as a Table in Microsoft Access and is named TBLPROJECTLOCATINFO_A. The steps for processing this data are as follows:

1. Modify TBLPROJECTLOCATINFO_A to include FY.

    a. FY is defined as July of the previous year to June of the current year (i.e. FY 2015 is July 2014 to June 2015)

    b. FY can be calculated by creating a new field in Access that uses an if statement to determine the Fiscal Year based on the date of the survey

2. Create a new table with the RCLINK of each project.

    a. Export TBLPROJECTLOCATINFO_A to Excel

    b. Create new column called RCLINK

    c. Create project RCLINK by concatenating other columns (COUNTYNO1%ROUTETYPE%ROUTENO%ROUTESUFFIX)

    d. Import Excel file as a Table into Access (TBLPROJECTLOCATINFO_B)

3. Create a new table that creates Project IDs.

a. Export TBLPROJECTLOCATINFO_B to Excel

b. Create new column called ProjectID

c. Create ProjectID by concatenating other columns (RCLINK%MILEPOSTFROM1%MILEPOSTTO1%MILEPOSTFROM2%MILEPOSTTO2%MILEPOSTFROM3%MILEPOSTTO3)

d. Import Excel file as a Table in Access (TBLPROJECTLOCATINFO_C)

4. Update TBLPROJECTLOCATINFO_C to replace blank MILEPOSTTO and MILEPOSTFROM to 0s.

   a. *Query*: UPDATE TBLPROJECTLOCATINFO_C SET MILEPOSTFROM2 = 0 WHERE [MILEPOSTFROM2] IS NULL;

   b. Repeat for MILEPOSTTO2, MILEPOSTFROM3, and MILEPOSTTO3

   c. Run the Update Queries

5. Create a calculated field called project length in TBLPROJECTLOCATINFO_C.

   a. Fields->More Fields->Calculated Field ->Number

   b. *Expression*: Abs([MILEPOSTTO1]-[MILEPOSTFROM1])+Abs([MILEPOSTTO2]-[MILEPOSTFROM2])-Abs([MILEPOSTTO3]-[MILEPOSTFROM3])

6. Remove all entries with Missing Project Ratings.

a. Create New Table From TBLPROJECTLOCATINFO_C called FINAL_TABLE

b. *Query*: DELETE * FROM [FINAL_TABLE] WHERE Rating IS NULL;

7. Remove all non-asphalt projects.

   a. *Query*: DELETE * FROM FINAL_TABLE WHERE NOT ((FINAL_TABLE.SURFACETYPE)="A" Or (FINAL_TABLE.SURFACETYPE)="B" Or (FINAL_TABLE.SURFACETYPE)="S");

8. Remove Duplicates and Bad Deterioration Trends from FINAL_TABLE.

   a. Manually check the ProjectIDs of each district, interstate and non-interstate and update in Access

   b. Import Tables with corrected ProjectIDs from Excel into Access

   c. Check each ProjectID for duplicates

      i. Find duplicates using FY and ProjectID as the matching criteria for a Query Wizard

APPENDIX D. TPMS FOR ALL PAVEMENT FAMILIES

Table 23. TPMs for Critical, Interstate families for 7 Working Districts

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.77236	0.22764	0	0	0
Good	0	0.69874	0.30126	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 2					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	1	0	0	0	0
Good	0	0.6667	0.3333	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 3					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.9695	0.0305	0	0	0
Good	0	0.53	0.4	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 4					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.861	0.139	0	0	0
Good	0	0.8986	0.1014	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 5					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.8928	0.1072	0	0	0
Good	0	1	0	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 6					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.9396	0.0603	0	0	0
Good	0	0.5976	0.4024	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 7					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.8234	0.1766	0	0	0

Table 23. TPMs for Critical, Interstate families for 7 Working Districts

Good	0	0.6666	0.3334	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1

Table 24. TPMs for High, Non-interstate families for 7 Working Districts

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.5947	0.4053	0	0	0
Good	0	0.5603	0.4397	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 2					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.8672	0.1327	0	0	0
Good	0	0.7219	0.2781	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 3					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.752	0.248	0	0	0
Good	0	0.6862	0.3138	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 4					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.75	0.25	0	0	0
Good	0	0.5828	0.4172	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 5					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7528	0.2472	0	0	0
Good	0	0.7268	0.2732	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 6					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7629	0.2371	0	0	0
Good	0	0.6062	0.3938	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 7					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.6647	0.3353	0	0	0
Good	0	0.6435	0.3565	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1

Table 25. TPMs for Medium, Non-interstate families for 7 Working Districts

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.5947	0.4053	0	0	0
Good	0	0.6732	0.3268	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 2					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7835	0.2165	0	0	0
Good	0	0.7223	0.2777	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 3					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.752	0.248	0	0	0
Good	0	0.6862	0.3138	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 4					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7789	0.2211	0	0	0
Good	0	0.7091	0.2909	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 5					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7873	0.2127	0	0	0
Good	0	0.7282	0.2718	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 6					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.6893	0.3107	0	0	0
Good	0	0.7866	0.2134	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 7					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.6082	0.3718	0	0	0
Good	0	0.6913	0.3087	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1

Table 26. TPMs for Low, Non-interstate families for 7 Working Districts

District 1					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.6433	0.3567	0	0	0
Good	0	0.7358	0.2642	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 2					
	Excellent	Good	Fair	Poor	Bad
Excellent	0.7967	0.2033	0	0	0
Good	0	0.7565	0.2435	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 3					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7557	0.2443	0	0	0
Good	0	0.8266	0.1734	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 4					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7407	0.2593	0	0	0
Good	0	0.74	0.26	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 5					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.7421	0.2579	0	0	0
Good	0	0.7741	0.2259	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 6					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.8545	0.1455	0	0	0
Good	0	0.7065	0.2935	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1
District 7					
	Excellent	**Good**	**Fair**	**Poor**	**Bad**
Excellent	0.5	0.5	0	0	0
Good	0	0.5401	0.4599	0	0
Fair	0	0	0.5	0.5	0
Poor	0	0	0	0.9	0.1
Bad	0	0	0	0	1

APPENDIX E. COPACES SEGMENT FIELDS COLLECTED

Table 27. Segment location field names

Field Name
TRIPDATE
ROUTENO
COUNTYNO
SEGMENTFROM
SEGMENTTO
SAMPLELOCATION
SEGMENTRATING
LANEDIRECT
LANENO
PROJECTLIMIT
CRACKWIDTH
CRACKSEALED
SEMENTREMARK
COUNTYRECORD

Table 28. Segment survey field names

Field Name
TRIPDATE
COUNTYNO
ROUTENO
SEGMENTFROM
SEGMENTTO
RUT_OUT_WP
RUT_IN_WP
LOAD_LEV1
LOAD_LEV2
LOAD_LEV3
LOAD_LEV4
BLOCK_PCT
BLOCK_LEV
REFLECT_NO
REFLECT_LEN
REFLECT_LEV
RAVEL_PCT

Table 28. Segment survey field names (Continued)

RAVEL_LEV
EDGE_PCT
EDGE_LEV
BLEED_PCT
BLEED_LEV
CORRUG_PCT
CORRUG_LEV
LOSS_PAVE_PCT
LOSS_PAVE_LEV
CROSS_SLOPE_LEFT
CROSS_SLOPE_RIGHT
PATCH_POTHOLE

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